Following the success of the first three meetings in Lisbon (1996), London (1999), and Treviso (2002), the European Commission and the Fraunhofer Institute for Systems and Innovation Research are organising the 4th International Conference on Energy Efficiency in Motor Driven Systems to be held in Heidelberg, Germany September 5th to 8th, 2005.

The previous EEMODS events have been very successful in attracting an international and distinguished audience, representing a wide variety of stakeholders in the development, manufacturing and promotion of energy-efficient motor systems.

EEMODS '05 will provide a forum to discuss and debate the latest developments in the impacts of electrical motor systems on energy and the environment, the policies and programmes adopted and planned, and the technical and commercial advances made in the dissemination and penetration of energy-efficient motor systems.

The conference’s technical focus is on industrial motors and motor systems, where the replication and savings potentials are the greatest.
Foreword

Motor driven systems account for about 65% of the demand for industrial electricity in Europe. If energy efficiency were given more priority in new plants or during refurbishments, Europe could save up to 202 billion kWh in electricity consumption every year. This would significantly reduce greenhouse gas emissions at zero or even negative costs, as improvement measures in motor driven systems are generally economical. Motor driven systems will therefore play a key role in bringing Europe on the road to the Kyoto targets.

Moreover, investing in energy efficiency will improve the competitiveness of European Industry, create new jobs and reduce Europe's dependency on fossil fuel imports. With continuously rising energy prices, additional profits from investments in motor driven systems are increasing too.

The fourth international conference on Energy Efficiency in Motor Driven Systems (EEMODS) will be held in Heidelberg, Germany, from 5 to 8 September 2005, to discuss the newest developments in this field of motor driven systems. This event, which is taking place in Germany for the first time after having been staged in Lisbon (1996), London (1999) and Treviso (2002), is being jointly organized by the European Union and the Fraunhofer Institute for Systems and Innovation Research in Karlsruhe.

Experts from all over the world from industry, research and policy-making will come together in Heidelberg to exchange views on the latest technological trends in motor driven systems, their market potential and environmental impacts. They will discuss the current developments in legal regulations, for example, directives on the eco-design of products and energy services in the EU, but also in other countries such as China, India or the USA, as well as voluntary commitments of industry or programs such as the Motor Challenge Program.

The conference will focus on motor driven systems in industry. Since the beginning of the conference series, it has become clear to all actors that looking at whole systems rather than single components will uncover the greatest saving potential in these systems. According to numerous studies, world-wide electricity consumption of motor driven systems could be reduced by about 20 per cent at payback rates of less than two years. Why not start now to take advantage of these potentials?

Karlsruhe, August 2005

Peter Radgen
EEMODS Conference Chair
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The International Copper Association, Ltd. (ICA), a not-for-profit organization, is the leading organization for promoting the use of copper worldwide. The 38 member companies of ICA represent more than 80 percent of the world’s refined copper output. ICA is responsible for guiding strategy and policy, and funding international initiatives that help deliver the benefits of copper in over 50 countries around the world. Headquartered in New York, ICA executes programs and initiatives through regional offices in Brussels, Santiago, Singapore, and New York, and through 27 copper promotion centers on six continents. ICA also underwrites extensive original research to develop a deeper understanding of how copper affects ecosystems and human health, as well as plant, animal, and human nutrition.

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ICA and its Sustainable Electrical Energy team are proud sponsors of EEMODS, recognizing the positive role of this conference and the contribution copper makes to enhance energy efficiency and performance of electric motors and motor driven systems. Electricity consumption by motor systems usually accounts for 25% to 70% of a country’s total electric energy use. Therefore, the business case for taking action, and setting or reinforcing policy in order to further improve energy efficiency, includes strong economic, social and environmental arguments.
Introduction
Welcome Address of the Mayor of the City of Heidelberg

Dr. Eckart Würzner, Mayor of the City of Heidelberg

Climate Protection

Climate Protection is one of the most pressing issues in international, national, and local politics, as emphasized by the World Summit in Rio de Janeiro in 1992. The city of Heidelberg, Germany, is well aware of this responsibility, and, in accordance with the November 7, 1990 resolution of the German federal government to reduce levels of Carbon Dioxide emissions by 25%, the city council passed a resolution in 1991 for implementation on a local level. As a starting-point, the city asked the IFEU institute to develop an „Action-oriented local conception for the reduction of climate-affecting trace gases.” This feasibility study proposed changes and actions in the areas of Energy and Transportation.

In accordance with the slogan „Global denken – lokal handeln“ (think globally, act locally) the campaign „Klimaschutz Heidelberg – gemeinsam gegen dicke Luft,” or „Climate protection in Heidelberg- acting together to combat dirty air,” started in 1992. Since then there have been numerous measures taken and projects implemented. The realization of these measures is documented regularly in Progress reports published by the city.

Solaranlagen auf Heidelberger Schulen – Solar Panels on the Heidelberg Schools

The Department for Environmental Protection, Energy and Health promotion, the facility management of the City of Heidelberg, and the SWH AG has installed Photovoltaic systems and solar-thermal installations on many roofs of the Heidelberg schools. Gradeschools, secondary schools, junior high schools (or secondary modern schools) and vocational schools use their roofs or facades, to warm water in an environmentally friendly way, or use sun energy to load electricity onto the electric grid. The solar panels are integrated into the project-work of the E-Teams and science classes at the schools.

Many of the Heidelberg schools are very active and have taken part in a solar model competition, building solar boats or solar boat models for the Heidelberg Solar boat Cup.

Climate Protection Concept

In 1992 the city drafted an energy plan that induced various and interesting initiatives. This energy control and climate protection programme focussed on municipal buildings and on private households, trade and industry.

- the growth of the energy-saving potential through technical improvement of energy-efficiency and consumer awareness, to develop new habits;
- combined production of heat and electricity;
• the recovery of waste heat and overproduction of electricity in trade and industry;
• the use of locally available energy potential and renewable energy sources.

Energy Table
To achieve a better communication with actors an „Energy round the table“ has been organised and bringing together residents, non-governmental organizations, local experts, associations and businesses. This provides them with a forum identifying and implementing energy management projects, based on local cooperation and particularly concerned with energy optimization when rehabilitating old buildings.

Green Electricity
In 2003 it is even stated that 25% of the electricity-consumption originates from green/environmental sources.

Energy Management in Municipal Buildings
Energy costs and CO₂ emissions could by reduced in the last 10 years around 35%.

Stromspar-Adventskalender – Day by Day, Energy Saved
With a „Day by day, Energy saved“ Advent calendar, the Environmental Department of the City of Heidelberg is campaigning for energy-saving appliances with the chance to win numerous attractive prizes.

The time of Advent, when the streets and houses sparkle with Christmas decorations and are brightly light, wish lists are written full of electric appliances like computers, televisions, and other household appliances, is the time to contemplate the energy used by a household throughout the past year.

To promote the responsible and economical use of Electricity, the Department of Environmental Protection, Energy, and Health Promotion of the City of Heidelberg, as well as other partners, have designed an Advent Calendar specifically about saving energy at home.

For each of the 24 Days of Advent, there is a tip for saving Energy, and, hidden behind the paper doors of the calendar, the chance to win attractive prizes. The main prizes are an energy-saving Television set, two energy-saving Computer monitors, a freezer and a combi Freezer-refrigerator, as well as gift certificates for energy-saving appliances, to be used at participating bakeries and for buying energy saving lamps.

The Advent Calendar is the prelude to an Energy saving campaign that will be conducted in the year 2005.
Participating Sponsors of the Energy-saving campaign:
The Guild for Electric and Information technology, the City Utilities Company, KliBA (Consultants for climate protection and emission reduction), Hornbach, Praktiker, Mediamarkt, The Bakerys Mantei, Gundel, and Riegler, the Schaffheutle confectionary, the Zoo of Heidelberg, The Children and Youth Theater of the City of Heidelberg, The Environmental Department of the City of Heidelberg, the Philharmonic Orchestra of the city of Heidelberg, The Heidelberg Solar Ship Society, The City Garden of Heidelberg, and Peter Haas Lenzhoftannen.

Niedrigenergiehaussiedlung

The low-energy house settlement „at the village” was initiated as part of the City of Heidelberg Campaign „Climate Protection Heidelberg: working together against bad air,” in order to demonstrate practical examples of energy savings and potential climate protection of ecological construction to construction workers, architects, and builders. The first pilot project in Heidelberg was the construction of a low-energy house complex in subsidized housing projects of the Association of Property and Real-estate in Kirchheim „in the village“. The 68 apartments in three low-energy buildings feature heat energy costs of less than 50 kilowatt-hours per square meter of living area and year (kWh/m²a). For a 50 square meter apartment, this means a yearly heat energy cost of only 200 Dm, as opposed to the usual 500 DM. The low-energy house shows the huge potential to save energy in new development, as well as a notable decrease in carbon dioxide emissions by 57,000 kg a year.

The project will be realized through close cooperation with the City of Heidelberg, the Association of Property and Real-estate, the Heidelberger Gerstner Architects, the city municipal utility (Stadtwerke Heidelberg AG), the IFEU institute of Heidelberg (Institute for energy and environment Heidelberg) and the Engineer office „ebök" , with the intent of demonstrating the feasibility of maintaining the high standard employed in the project as well as achieving the lower rent prices of social project building. The apartment building has been moved in 1996.

At the core of the energy-saving-concept of the low-energy house is excellent insulation and the prevention of heat-bridges in the joints of the individual components, as well as tightly controlled ventilation and heating. The heating is provided by the Heidelberg AG „Natural-Gas Heating service" in a condensing boiler, that compared to a normal low-temperature condensing boiler saves 10 % energy. In addition, the Stadtwerke Heidelberg AG installed a solar- collector device that in summer provides most of the heating of water, and throughout the year provides 40% of the heating of water. In solar collectors with a surface area of 170 square meters sunlight is transformed to heat, which is then pumped into a 6,000 litre collecting tank. The solar collector is also a component of the roofing of the house, and lends a creative accent. The ecological concept of the house is rounded out by a rain-water collector, through which the rainwater coming from the roof of the house is collected in an underground cistern and used to flush toilets and to water the gardens.
All of the exterior portions of the house, such as balconies, and arbors are physically and thermally separated from the main building. There are no rolling shutter boxes in the exterior walls, but instead sliding wood shutters that are mounted on the thermally disconnected balcony.

The massive stone external walls exhibit an outlying damp course of 16 to 18 cm thick. To avoid the uncontrolled loss of heat, structural damage, and as a condition for the integration/assembly of a ventilation system, the shell of the building must be airtight. All of the apartments are equipped with a controlled exhaust device, through which a considerably better interior air quality coupled with a minimum loss of heat can be achieved.

All connecting units, especially between window frames and walls, and between walls, roofs, and ceiling as well as pipe (connections) are tightly sealed. Building materials containing PVC and CFCs (chlorofluorocarbons) as well as exotic woods are, as a rule, avoided. Wood is the building material used for the windows, except for in special cases where a wood-aluminium composite material is used.

Ecological building and living is not just vitally important for the Environment and our Quality of life. Lower heating costs are one of the many advantages of the low energy house construction, because a very good insulation and careful avoidance of heat bridges lowers the heat energy requirements.
Innovation and Research in the Energy Sector

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*Paper not available at time of printing.*

*Will be available online at [www.eemods.de](http://www.eemods.de)*
The European Motor Challenge Program

Paolo Bertoldi, European Commission, DG JRC, Ispra, Italy

1. Abstract

Electric motor driven systems account for the greatest part of industrial electricity consumption in Europe. Numerous studies on individual component (motors, pumps, compressors) and on the consumption characterisation have shown the considerable potential for improvement of energy efficiency of these systems, and have recommended suitable policy actions.

A number of policies have succeeded in making improvements on the supply side for individual components of systems, such as the electric motor itself. For electric motor a EU wide classification scheme and labelling exist together with a voluntary agreement by motor manufacturers to substantially improve the efficiency of motor placed on the market.

Following the recommendation of experts, the European Commission decided to that a concerted effort on the demand side could very usefully complement the efforts being spent on components and technologies. The European Commission has decided to launch „The European Motor Challenge Programme“ (MCP). This is a voluntary programme for motor systems end-users to agree to look at their motor systems and to carry out within a specific time frame the savings measure that are economic.

The paper describes the programme and its implementation. The programme is based on the analysis of the main reasons why profitable energy savings measures are not put into practice in the private companies and on the successful examples where high level management made the necessary decisions to carry out motor systems energy efficiency programmes.

The essential elements of this programme are:

- to raise awareness among industrial and service sector users of motor systems about the potential for energy saving (and money saving) measures;
- to create a European wide framework to encourage top-level decision makers to make the implementation of these energy savings measures a management priority.
- to make available a wide range of information tools based on the EuroDEEM database, to aid users in optimally designing, purchasing, installing and operating motor driven systems;
- to get clear commitment by the company top management to carry out efficiency measures in motor systems.

The publicity aspect of the programme would be used to convince top management of the usefulness of subscribing to the MCP „Guidelines“, in some ways similar to the existing EU „GreenLight“ Programme commitment. Because of the very wide variety of situations, this commitment is open ended and flexible, a sort of „variable geometry“.
system, where each company, with aid from national energy agencies (the MCP „Na-
tional Contact Points”) the Commission, would target those areas and measures most
likely to be effective in its operations. The company will commit to carrying out these
measures, and reporting on the results, within an agreed upon time period.

2. Introduction

Electric motor driven systems account for 69% of industrial electricity consumption in
Motor electricity consumption in the industrial and in the tertiary sectors in the EU in
1998 was responsible for 69% and 38% of the total electricity consumption, accounting
for 590TWh and 190TWh respectively.

Figure 1 shows the share of motor electricity consumption by end use in the industrial
and in the tertiary sector in the EU-15.

Numerous studies and projects have shown the considerable potential for improvement
of energy efficiency of these systems. The electricity savings potential are estimated for
the year 2015. The annual average growth rates of the electricity consumption up to
2015, in the industrial and in the tertiary sector is assumed to be 1.2% and 1% respec-
tively. A more recent study coordinated by the European Copper Institute (de Keule-
naer) estimated savings of 202 TWh per year for the EU-25, equivalent to electricity
cost savings for industry in the range of 5 to 10 Billion Euro.

For the estimation of the motor electricity and carbon savings potential, the efficiency
improvements considered, are the application of Energy-Efficient Motors (EEMs), Vari-
able Speed Drives (VSDs), and energy efficient end-use devices and sytems (pumps,
fans and air compressor systems). The total technical and economic electricity and
CO₂ savings potential in Industry and in the Tertiary sector in 2015 are presented in
Table 1:
Table 1: Total final technical and economic electricity and CO2 savings potential in Industry and in the Tertiary sector by 2015

<table>
<thead>
<tr>
<th></th>
<th>$TWh$ Savings by 2015</th>
<th>$CO_2$ Mtons Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technical</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Industry</td>
<td>107,1</td>
<td>42,9</td>
</tr>
<tr>
<td>Tertiary</td>
<td>36,7</td>
<td>14,7</td>
</tr>
<tr>
<td>Economic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Industry</td>
<td>84,3</td>
<td>33,7</td>
</tr>
<tr>
<td>Tertiary</td>
<td>24,5</td>
<td>9,8</td>
</tr>
</tbody>
</table>

The above estimated savings potential would be higher if other efficiency improvements would be included. The application of low cost efficiency measures which do not require sophisticated technology, such as improving maintenance practices, reducing waste, switching off the equipment when it is not being used (for example for the case of belt conveyors), would lead to large savings. These „Housekeeping Measures“, deserve to be strongly publicised among motor users. Drive-train and connection systems are another possibility for efficiency improvements (gears, belts, chains and bearings). Losses in the power transmission system are often surprisingly large, but carefully selection and maintenance of drive-trains and their components are crucial for improving energy efficiency.

Figure 2: Economic Savings potential in Industry by 2015

A number of programmes have succeeded in making improvements on the supply side for individual components of systems, such as the electric motor itself. For electric motor a European classification scheme and labelling exist together with a voluntary
agreement by motor manufacturers to substantially improve the efficiency of motor placed on the market.

![EUROPEAN EFFICIENCY STANDARDS FOR AC INDUCTION MOTORS](image)

Figure 3: EU/CEMEP Motor Efficiency – Classification scheme

A similar action has been introduced for pumps for clean water, the so called procurement lines. It appears that a concerted effort on the demand side could very usefully complement the efforts being spent on components and technologies. The essential thrust of such an effort would be to:

- raise awareness among industrial users of motor systems about the potential for energy saving (and money saving) measures;
- make available a wide range of information tools, to aid users in optimally designing, purchasing, installing and operating motor driven systems;
- create a European wide framework to encourage top level decision makers to make the implementation of these energy savings measures a management priority. This framework could adopt some of the successful elements of similar programmes, such as the European Union GreenLight programme, or the US DoE Compressed Air or Motor Challenges.

There are multiple reasons that explain why profitable (sometimes very profitable) energy savings measures are not put into practice in the private sector:

- Motor systems electricity consumption is „invisible“ to top management, since it is most often a relatively small cost item for any one company.
- Electricity consumption in general, and motor systems consumption in particular, is usually treated as a general overhead item in company analytical accounting.
Introduction
The European Motor Challenge Program

schemes. Thus reducing this cost item is not the responsibility of any particular manager.

- Measures to optimise the cost of equipment purchases, such as competitive bidding procedures, rarely take into account long term operating costs due to electricity consumption. Thus these cost cutting practices can be counterproductive in terms of reducing life cycle costs for electricity. This is particularly true since the optimal systems according to the electricity consumption criterion often require higher initial investment. Thus they are not even proposed by suppliers in competitive bidding procedures.

- Responsibility for potential optimisation measures is largely diffused among several management functions: Production, Maintenance, Purchasing, Finance. It is difficult to get high-level management agreement, cutting across departmental responsibilities, on a low priority item such as electricity consumption.

Despite all these difficulties, in those cases where high level management makes the necessary decisions to carry out motor systems energy efficiency programmes, the results are often outstanding, and management retrospectively is happy with the decision. Many European Union and Member State programmes have focused on the problem, and have had some success in stimulating the necessary high level consideration of the problem.

The „Electric Motor Driven Systems“ considered in the MCP are the typical fluid handling application such as compressed air, pumping or ventilation (and in future will also include commercial refrigeration). These applications have in common:

- an electric drive (consisting of a motor and perhaps an electronic motor controller) which converts electrical energy into mechanical energy in the form of a rotating shaft;

- a second conversion device (compressors, pumps or ventilators) which use the mechanical energy delivered by the drive to displace and/or compress a working fluid;

- a network through which the fluid circulates. (In compressed air systems, this network may terminate with an end use device which again transforms the mechanical energy in the air into some other type of service);

- some kind of control mechanism to adjust the output of the system to the needs of the application.

For the purposes of energy efficiency, it is essential to note that the overall efficiency of these fluid circulation applications depends of course on the efficiency of the drive and of the conversion device. It depends even more on the design and operation of the networks of which they are a part, and the inter-relationships between the components. For this reason, the MCP will mainly address the systems, and not only the individual components.
3. The Framework of the Motor Challenge Programme

The first activity has been to establish the basic elements of the MCP including the Guidelines. As the GreenLight programme as demonstrated, is expected that this will be an iterative process, and that experience from the early phase of the programme will be used to correct and improve the proposed Guidelines.

The purpose of the Guidelines is to define the nature of the commitment of companies, which choose to participate in the Challenge Programme, and the requirements, which have to be fulfilled by participants. While the Challenge Programme must be sufficiently flexible to accommodate diverse situations, the general requirements of the approach must be sufficiently rigorous so that the commitment to the Guidelines is meaningful and results in energy savings. Thus, the commitment must contain clearly defined and verifiable actions, which the companies will carry out. These actions must be of such a nature, that they will lead to realising the bulk of profitable energy savings measures in plants of participating companies. The actions will include:

- a public Commitment, including internal communication of this Commitment;
- integration into management procedures of those reporting and evaluation mechanisms necessary to verify dissemination of the MCP action within the company;
- inspection, audit and reporting procedures, to allow top level management to control energy consumption;
- integration of energy consumption criteria into design and purchasing procedures (including, for instance, „Life Cycle Costing“).

The MCP is based on a number of „building blocks“ covering three of the main types of motor driven systems (Compressed Air, Pumping and Ventilation Systems)\(^1\), for which major energy savings potentials exist.

A specific building block will address the horizontal elements such as motors, transmission element and adjustable speed drives. The use of high performance motors and of electronic motor controllers are common elements to all motor driven systems and can in any case lead to substantial energy savings. The wide experience already gained through the use of EuroDEEM database together with the motor classification scheme would play a major role in the construction of this block.

The basic element of the building block will be to define the technical nature of an appropriate commitment for the specific type of motor driven system. Because of the very heterogeneous nature of these systems, and the diversity of specific company installa-

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\(^1\) These three applications account for about half of industrial energy consumption, and an even larger percentage of the savings potential. It has now been decided to include also refrigeration systems in this project because large refrigeration systems are common to both service and industry. Thus it would appear logical to treat them in the Motor Systems Challenge. For the service sector activities, i.e. commercial building a very similar programme is operating in Europe the GreenBuilding programme.
tions, the “building block” must specify a general approach, consisting of verifiable actions, which when carried out lead to optimal system functioning.

Previous European Commission studies of compressed air systems, pumps, ventilators, motors, electronic motor controllers, have already identified the savings potentials of technical and organisational measures.

The building block must define the notion of a “profitable energy savings measure”. It is clear that this cannot be limited to lowering cost, but must include reliability and quality of service criteria. One important consideration is that the targeted types of systems (compressed air, pumping, and ventilation) are usually considered as “technical services” within a production facility. Their failure, or a drop in quality of service, can have catastrophic results on production. Thus, from an industry management point of view, reliability and quality of service are the overriding criteria for judging the cost effectiveness of the service, rather than the actual cost of producing the service. For this reason, the Challenge Programme Guidelines will clearly state that profitable energy savings must maintain or improve reliability and quality.

4. The Guidelines

The MCP Guideline will contain an overall framework for the 4 “building blocks” already described. The framework will be modular, so as to permit the incorporation, in the future, of new building blocks (for instance on refrigeration systems).

The framework must be of an „à la carte“ nature, that is to say that companies must be able to choose the elements or types of systems relevant to their operations. This in general means that a company will commit to examine those types of motor driven systems (compressed air, pumping and ventilation systems) that are large energy users in its plants. Some companies might also choose a transversal approach focused on the drives: high performance motors or adjustable speed drives. Furthermore, the framework must be compatible with the range of approaches of the Member State Energy Efficiency programmes for electric motors systems.

In any case it is not be possible to specify quantitative requirements for energy savings (as is the case for the GreenLight programme), since the level of savings possible depends on the precise nature of each installation and given the wide range of applications. Rather, the target for energy savings must be determined as a part of the audit process to which the company commits itself when signing on to the MCP.

The Guidelines will define the process by which companies commit to the MCP, define their specific company plan, carry out their plan and evaluate the results.

Since the process is similar to other environmental and quality certification methods such as ISO 9000, ISO14000 and EMAS, care has been taken to use elements from these methods so as to simplify and reduce the cost of committing to the programmes.

The guidelines will be accompanied by the following documents, initially available in English, and in some national languages:
• awareness raising material to help top company deciders understand the purpose of the MCP and the potential for energy savings. Special attention will be paid to the reliability and quality of service criteria;

• guidelines for the audit and implementation processes, including initial measurements and ex-post evaluation procedures;

• lists of resources (co-operating equipment manufacturers, engineering consultants, software, documents and books, training material, list of possible financing mechanism, list of ESCOs operating in this field, etc.).

As it was experienced with the GreenLight Programme, initially there will an ongoing and permanent manner to improve the MCP. Thus, it is to be expected that more than one working version of Guidelines will be issued during the course of the programme, leading to a consolidated version about three years after the launch of the programme. The first two years were used to test the overall MCP concept, and this phase contributed to improving and validating the MCP Guidelines.

5. The Programme Implementation

5.1 Negotiate participation of industrial enterprises

Perhaps most difficult task of this phase will be to obtain the agreement of companies to participate in the programme. Since at this stage, the MCP will is not well known and publicised, programme participants will not have incentives to participate, including the benefit of the full scale public information campaign. Nor will there be „name recognition” for the Challenge Programme, nor for the logo that is associated with it. It is to be expected that many companies will adopt a „wait and see” attitude with respect to an approach that will be new and untested.

It will thus be necessary to use the full political weight of the European Commission and of the National Energy Agencies („national promoter”) to convince companies to serve as test beds for the programme.

Each national promoter will seek to obtain the agreement of some key company during the first three years. These companies have been chosen by each promoter as a function of national priorities and programme constraints. Although the Challenge Programme will ask companies to involve all of their major production facilities, during this pilot test phase, the commitment will most likely be for only one plant, and perhaps for only one service (pumping, compressed air, ventilation).

According to the procedures set out in the Guidelines, the commitment will specify the types of motor systems that will be covered by project activities. The Guidelines should also specify that the results of the MCP may be made public in order to further the aims of the Challenge Programme. In some cases, this will necessitate negotiation on the nature of information to be made public, in order to protect industrial secrets.
5.2 Carry out audits

The National Energy Agencies, in accordance with the terms of their particular national programmes, helped companies with the initial audits during the first year to stimulate company participation. The audits shall include description and measurement of the initial state of the motor systems, so as to permit ex post evaluation of the success of actions carried out. The audit recommendations must of course respect the „Reliability“ and „Quality of service“ clauses of the Guidelines.

In some countries public funds can be used to co-finance some parts of the audit process, in order to incite companies to participate in the pilot phase. In some countries, this is done within the framework of existing audit programmes. To offer help for the audit is a key policy to achieve energy savings, as companies do not believe that saving exist and thus are reluctant to invest „little“ money to carry out an audit. Some countries have mandatory energy audit for the industrial sector this is a very important policy measure to stimulate energy efficiency.

5.3 Accompany enterprises in implementation

The complete implementation of the Guidelines and of the audit recommendations will probably take much longer than the programme. This is because many of the recommendations will bear on design and purchasing decisions for the creation, renewal or upgrading of major systems. Some of the major components (compressors, pumps, ventilators, piping and ducts, etc.) are replaced in 10 to 20 year long cycles. It is thus likely that many of the recommendations will not have been carried out during the life of the MCP programme, which is initially limited to five years.

However, at a minimum, the participating company would have put into place:

- those improvements for maintenance and operations procedures for which rapid implementation is technically feasible (for instance leak detection programmes for compressed air systems, and energy efficient drive belts in ventilators drives);
- some retrofit operations, when they are technically feasible and have very short payback times;
- the basic architecture of a management structure to carry out the plan in the long term. This would include:
  - tools for internal communication on the objectives of the companies commitment to the Programme;
  - guidelines for the integration of energy considerations into purchasing procedures (in particular appropriate elements of Life Cycle Costing).

5.4 The information campaign

Participating national energy agencies will develop prototype information campaigns. The agencies will:
- define the way in which the MCP message can be best adapted to national circumstances;
- develop the message to be delivered to the national companies. In particular, by adjusting the European message to correspond to the specific national energy efficiency programmes;
- identify the best vectors to touch the target group of high level industry management;

6. The Challenge Programme Web-site

The technical basis for the MCP (identification of the technical measures necessary, auditing procedures, measurement tools, etc.) have been established in previous European programmes. A key contribution to gathering all this information will be made through the EuroDEEM database and web-site.

The European Commission has developed a European database for motor system, called EuroDEEM. This activity started in 1995 with the design of a tool for the promotion and selection of Energy Efficient Electric Motors (EEM). The scope of the database containing electric motor data was to make available an important information tool that allows users to easily carry out an evaluation of the best installation or replacement options, therefore helping the promotion of electricity efficiency. The EuroDEEM software package will permit users to select the most suitable electric motor for their purposes, evaluating energy and financial savings.

The first version of EuroDEEM containing only the motor selector database was completed and realised in 1998 with about 3000 motor models available on the EU market. The motor data are loaded directly from motor manufacturers.

EuroDEEM has been created to be a complete tool for very wide promotion and dissemination of information about energy efficiency in motor systems to a large range of end-users.

EuroDEEM included in 1996 the Motor System Inventory Database for keeping track of all motor systems and electricity consumption in a Company. Utility data and tariff.

In 1998 it was decided to expand the database to other important motor system components such as Variable Speed Drives (VSDs), pumps, compressors, fans and other transmission and control devices.

Development activities for the pump and VSD module have started in 1999. A first Demo version of the pump module is available.

In year 2000 a motor system audit procedures has been developed and it has integrated in EuroDEEM.

The Challenge programme web-site helps in outreach for the Programme, and to provide specific technical information on energy efficiency measures for European companies. It also helps users to easily access the distributed elements of the information.
centre, lodged at National Energy Agency sites, trade association sites, equipment producer or distributor sites, etc. Existing tools to aid in optimal decision making in the design, purchase, installation and operation of motor driven systems will either be referenced, or where possible integrated into the information centre. It includes references to many different types of resources.

The web-site also contains a list of resources that could aid companies in achieving the potential energy use savings, while maintaining or improving reliability and quality of service. The lists includes specialised software, written material (journals, articles, books), multimedia training supports, etc.

6. Expected Results

To the MCP was allocated a budget of 1 billion € for the first two years. A third of this amount was spent in energy audits. The budget directly finances at least 12 energy audits and follow up on efficiency measures. Experience shows that industrial energy use audits catalyse decision making on technical measures with a value approximately 10 to 20 times the value of the audit. Thus, the project should stimulate at least 3 billion Euros of energy efficiency investments.

The long term effect of the programme would of course be much greater. The average payback time for the type of energy efficiency measures that the programme aims to encourage is under 2 years\(^2\). Thus the investments directly stimulated by the programme should permit over 2 000 000 Euros of annual energy savings, equivalent to well over 20 000 MWh in annual savings.

The MCP directly aims to create the conditions for an energy efficiency commitment by top level management in industry. Experience in the American “Compressed Air Challenge” is that the original target of 15 to 20% energy savings will more than be met. It may reasonably be hoped that a broader scale European Programme would be equally successful.

The benefits of a successful MCP would be very substantial. A conservative estimate would be 10% of industrial electricity use, i.e. about 70 TWh per year to be achieved after the five years life of the Programme.

\(^2\) Note that 2 year payback time, while typical of current industrial practice, is nonetheless a pessimistic estimate. It is hoped that the decision criteria of industrial enterprises will evolve (in part because of the Challenge Programme), so that longer payback time measures will be implemented. The use of Third Party or ESCO financing could play a role.
8. References


Introduction
Energy Saving Potential in Motor Driven Systems

Energy Saving Potential in Motor Driven Systems

Dr. Edwin Kiel (Chairman of the ZVEI working group drives), Lenze AG, Aerzen, Germany

The manufacturers of electrical motor systems and their customers, mainly the machinery industry, play a key role in saving energy. Electrical motor systems count for two thirds of industrial power consumption. The economic potential for saving energy has been largely explored as far as the electric motors are concerned. But there is still a huge potential for saving energy by using electronic speed control and by optimizing the processes of motor driven machinery.

A lot of European studies already investigated the energy saving potential in motor driven systems. The SAVE-study as for instance initiated by the European Commission estimates an energy saving potential of an equivalent of 40 Millions tons CO2 per year in Europe. Out of this total value 60% can be achieved by the application part (pumps, fans, compressors). 30 % by variable speed drives (VSD) and 10 % only by energy efficient electric motors.

The German motor and drive industry has been promoting energy efficient motors and drive systems for many years. The results are very successful. The sales of energy efficient motors and motor systems are growing year by year. One of the successful campaigns is the Voluntary Agreement between the European motor manufacturers and the EU-Commission lounged by ZVEI and CEMEP in the year 1998. This agreement led to a share of 80 % of energy efficient electric motors out of the total number of motors sold in the EU.

Another successful ZVEI campaign is the promotion of electronic speed control of pumps, ventilators, compressors and other applications where the substitution of mechanical process control leads to substantial energy savings. Today 30 % of electric motor systems sold in the German market are provided with electronic speed control. While the number of industrial motors sold is more or less constant, the number of electronic drives is increasing by more then 10 % each year.

Nevertheless there is still a great number of energy wasting old electric motor systems running in industry and public applications. The German drive industry in ZVEI is continuing its efforts to promote energy saving solutions in old and new installations. They appreciate every political support like the new EUP directive as long as it does not disturb free trade, competition and freedom of technology development und does not charge the industry with unnecessary administrative work and costs.

The German manufacturers of Motors and Drives in the ZVEI very appreciate the EEMODS Conference and its contribution to the promotion of energy efficient motor driven systems. They wish the Conference and the organizing people a successful event.
Observed Climate Change and Required Climate Policy

Prof. Hartmut Graßl, Max Planck Institute for Meteorology, Hamburg, Germany

*Paper not available at time of printing.*
*Will be available online at [www.eemods.de](http://www.eemods.de).*
Activities of CEMEP to Promote Efficient Motor Driven Systems

Jürgen Sander, President of CEMEP, VEM Motors GmbH, Wernigerode, Germany

Voluntary Agreement of CEMEP

In 2003 the very successful Voluntary Agreement of CEMEP (VA) terminated after a period of 5 years. During these five years, the VA was signed by 36 motor manufacturers in order to classify their standard motors and with the intention to launch energy-saving motors in the market.

The original target of this agreement, to reduce the market penetration of EFF3 motors in their joint sales by 50 percent, was so comprehensively achieved that the percentage of EFF3 motors decreased from 68 % in 1998 down to 8 % in 2004.

The sale of energy-saving motors (class EFF1 and EFF2) has increased to nearly 90 percent at the end of 2003. This positive development was possible because of investments and efforts by the European motor manufactures and intensive promotion of CEMEP. The EFF-logos are an established standard of quality and a marketing instrument for energy-saving products today.

The following diagram shows the development of 2 -and 4-pole motors in the European market since 1998.
Introduction
Statement of CEMEP

Since 1998, the participants of the Voluntary Agreement have sold almost 20 million motors in the scope of the VA in Europe and they continue in labelling and sales activities.

The higher market penetration of EFF2 motors was achieved by great efforts of the motor manufacturers only. But, up to now, they did not have the possibilities to raise the market penetration of EFF1 motors significantly, because of their price, which is in comparison to an EFF2 motor about 20% - 30% higher.

The reason for the higher price is the result of almost 20 – 30% more needs of material (e.g. steel, copper) and moreover high quality material as shown in the L'Aquila-Study.

Although the life-cycle-cost shows, that prime investment costs for new installations will be amortized by the energy saving benefits in a short period, customers are often not ready to pay higher prices. This deficiencies in energy-saving way of thinking is very often due to the fact, that the motor buyers (i.e. the OEMs) are usually not identical with the motor users, and they are therefore less interested in the energy-saving features of such EFF1 motors.

Each year the motor manufacturers sell about 3 millions of energy-saving motors in Europe. This development leads to a decrease of conventional motors in the European market and the energy saving steadily increases each year. A total sum of about 4.5 TWh could be saved in 2004 in comparison to 1997.
Renewed Voluntary Agreement of CEMEP

The European motor manufacturers and CEMEP are aware of their strong responsibility for the environment and are going to continue their efforts to launch energy-saving solutions on the market. Thus CEMEP goes on in two steps:

- To renew the Voluntary Agreement and go on its main features and to work on its weak point „the lack of control and supervision“. The renewed VA will be connected with the launch of a control system.

- To work intensively on the effects of the EuP Directive on motor driven systems. The focus will set on the ecological & economical optimum of motor driven systems. This work can be done only together with all market partners (OEM, distributors, manufacturer, end-users, system integrators, European commission)

Saving potential in motor driven systems

A lot of studies, like the SAVE-studies, show that the saving potential in motor driven systems can only be fully achieved, if all aspects of the system are involved.

Although the payback time for energy-saving investment would be amortized during the lifetime, customers that do not take direct advantage of the energy savings, are not prepared to pay for it.

Activities of the European Commission like the Motor Challenge Program are helpful, but there are more efforts needed to convince end-users and system integrators of energy saving. Tax-allowance for energy saving projects could be a successful instrument.

But, additionally, the CEMEP proposes to include OEMs and motor distributors into the scope of the Voluntary Agreement. By this way, there is a continuous information flow about the energy-saving idea of the motor manufacturers towards the end-users of motor-driven equipment. The end-users, with their knowledge about the motor operational hours, the energy consumption of their plants and equipment, are the favourite partners of the motor manufacturers to increase the energy savings and to launch the wider use of EFF1 motors.
The Proactive Role of the Pump Industry in the Field of Energy Efficiency in Motor Driven Systems

Dr. Paolo Marinovich, President of Europump / CEO, ITT Industries Water Technology Europe, Montecchio Maggiore, Italy

Distinguished Participants and Guests, Ladies, Gentlemen,

Europump, the organisation I have the honour and the task to chair at this time, is delighted to have the privilege of endorsing this important event and I would like to thank the European Commission and the Fraunhofer Institute for Systems & Innovation Research for the opportunity to say a few words at the opening of this plenary session.

I would like to underline what in Europump’s and my own personal view is the importance today of the 4th International Conference on energy efficiency in motor driven systems.

The European Union, this growing continental Institution to which we belong, has expanded its horizons in 2004. However, the Union has been hit by recent political difficulties in ratifying the Constitutional Treaty of December 2004. This has underscored the absolute need to restore the spirit of the European Council declaration of March 2000 in Lisbon, which challenges Europe

„to become the most competitive and dynamic, knowledge-based economy in the world, capable of sustainable economic growth with more and better jobs and greater social cohesion.”

Yes, a knowledge-based economy as a basis of a shared well-being within our nations and beyond. How can we, the world of industry and technology, contribute to this? Knowledge can only be generated through concept, design, experience and learning. Innovating and search continuously for better solutions.

Europe continues to be confronted with two other strong economic poles: on one side, the Unites States, with its relentless drive for innovation and progress, sustained by massive investments; on the other side, the rising economies of the Far East, China and India: different countries, different cultures, but very competitive costs of labour, increasing technical qualifications and mastery of technology, particularly in our sector.

Pumping water or other liquids is among the most common operations in industry and sounds like „obvious”. Obvious, however, is not „how” you do that, in order to spend the least possible of energy, avoid generating waste or cause situations that can be harmful to the people and to the environment. Here is the challenge that Europump has undertaken: understand more and more about these problems, through the experience of the pump users in the various applications and geographical areas, in order to be able to help the industry stay competitive worldwide.

This task needs to be accomplished also at the institutional level. We need to promote energy efficiency and environmental protection, however without an excess of compul-
sory rules, which would impact on the producers as well as on the users of rotating machinery. It is not an easy task, if you consider the multitude of applications known in industry and the different traditions existing in the various countries.

Efficient products, clean solutions, safe operations, best life-cycle cost: this is in essence what we, as European pump manufacturers, want to offer. Understand the needs of our customers; create with them the knowledge necessary to respond to the demands of the applications and anticipate their evolution. Europump members are committed to more transparency and information for their customers concerning the technological and environmental performance of their products. However, the information a manufacturer can provide to a potential customer cannot be standardised for all pumping systems. An installation is the result of specific needs or demands of the customer, and the efficiency of a component depends on its final use in the system as a whole which must also be properly designed.

Europump strongly supports the development and promotion of energy efficiency programmes such as the Motor Challenge and other energy efficiency voluntary measures, which offer the necessary flexibility and potential to educate our customers and users on energy efficiency, and which lead to results which can be monitored, verified and made publicly available.

On the side of educational initiatives, Europump and the Hydraulic Institute of the USA published the guide books on Life Cycle Costs of pumping systems and on Variable Speed Pumping.

In the effort to raise the awareness of the energy saving challenge and in order to present Europump as the representative of a responsible industry, the Association supported and endorsed the self-commitment of four European manufacturers of circulators to label their products according to energy performance classes. In addition, Europump has undertaken the task of monitoring the compliance to this commitment and ensuring its publicity.

Finally, for several categories of pump systems, Europump foresees the adoption of various guidelines, tools and new standards to improve significantly the energy efficiency and environmental impact of pumps and pumping systems during their installation as well as their operation in various market segments. This initiative is called ECOPUMP and all actions under this initiative will be flagged with the new ECOPUMP logo.

The ECOPUMP initiative aims not only at achieving eco-efficiency of pump systems but also at communicating the Europump efforts to:

- all customers or end users of our industry and, in this way, increase their awareness of energy consumption and environmental protection;

- Government institutions and stakeholders at the European Commission and Member State level in order to express the preference of our industry for voluntary commitments rather than legislative measures.
Introduction

Statement of EUROPUMP

Over the coming years, Europump will continue to identify market segments where changes can be made in order to encourage more energy savings and better environmental protection.

This event in Heidelberg is an outstanding opportunity for all participating engineers and industry managers to meet and enhance cooperation. You will witness presentations of very valuable work. This work represents the contributions of all committed stakeholders who have put their intelligence and their efforts at the service of progress and have been willing to make their knowledge a shared resource.

On behalf of Europump and myself, I would like to express the confidence that this knowledge will make the users’ and the producers’ activities more rewarding and this event a very significant step in support of progress, in Europe and beyond.

Paolo Marinovich
President
Brussels, 17 June 2005
The Proactive Role of the Compressed Air Industry in the Field of Energy Efficiency in Motor Driven Systems

Peter Seroczynski, President of PNEUROP, Ingersoll Rand European Sales Ltd, Wigan, United Kingdom

Good Morning Ladies and Gentlemen,

My name is Peter Seroczynski of Ingersoll-Rand European Sales Company, and I am also the current President of PNEUROP.

Pneurop is the European Trade Association for Compressed Air Equipment, Pressure Equipment, Air Treatment, Pneumatic Tools, Vacuum and Process Compressors. Its members are the National Trade Associations. There are currently 10 member associations which represent all the major manufacturers of the aforementioned equipment. The market value of the equipment and services provided is Euro 20.4 billion.

Compressed Air is viewed as the fourth utility after electricity, gas and water; and as such it is used in almost all industries. In fact, compressed air takes account of 10% of the industrial electricity consumption. In the European Union this amounts to over 80 tera watt hours per year.

Many of the Compressed Air Systems have been installed for many years, and from a recent survey in the European Union, which was supported by the European Commission, it was found that efficiency savings up to 50% can be achieved. In fact, the average system savings were 32.9% which is a massive energy saving potential for industry. The greatest potential for energy saving can only be achieved if the whole compressed air system is addressed. This potential will be further addressed by the various speakers over the next two days.

Pneurop supports and advances the safe and efficient use of its equipment and systems by its worldwide customers. It also promotes the most effective solutions to meet the environmental concerns of the countries where our equipment and systems operate. Complex systems such as compressed air systems are difficult to incorporate into legislation. The European eco-design of energy using products framework directive is mainly oriented towards products or components.

Raising awareness of decision-makers, auditing of existing installations and training of users as foreseen in the European Motor Challenge Programme, the UK training programme and the German Druckluft-effizient and system efficiency campaign are other initiatives for finding ways to increase energy savings.

Pneurop welcomes and supports the 4th International Conference on energy efficiency in motor driven systems organised by the European Commission and the Fraunhofer Institute for System & Innovation Research. We look forward to the programme and the various presentations, which will be of great interest to all users, service providers and equipment manufacturers.

Peter Seroczynski, President, Brussels, 17 June 2005
The Role of Air Conditioning and Refrigerating Industry in the Field of Energy Efficiency in Motor Driven Systems

Sulejman Becirspahic, Director of Operations of Eurovent/Cecomaf, Paris, France

Eurovent/Cecomaf is Association of 15 European National Associations of manufacturers of Air Handling, Air conditioning and Refrigeration Equipment. The Association represent more than 800 companies with a total turnover in excess of 20 billion €.

The essential activity is organised through working groups where manufacturers of a particular type of products meet together, examine relevant issues and decide actions to undertake.

Working groups for fans, liquid chilling packages, air conditioners, fan coil units, air handling units, air filters, refrigerated display cabinets are particularly active having usually several meetings a year. A number of application documents, guides, recommendations and other agreements have been finalised and published.

A very important feature of Eurovent organisation is the existence of the certification programmes. Eurovent certification covers a large part of relevant products and more than 180 manufacturers participate in one or more programmes. Checking data claimed in catalogues is extremely important as it was shown by testing in independent laboratories that there are always actors on the market not respecting clarity and honesty in data presentation. For instance a decision on minimum efficiency for a particular equipment if not supported by certification will not be applied by all manufacturers and distributors. Only regular checking by an organised system will guarantee the application.

As all products in the scope of Eurovent/Cecomaf consume energy – mainly in the form of electricity, the energy efficiency – intrinsic to the products but also related to use and installation – has become one of the most important issues for our industry. The implementation of the Kyoto protocol has now a high priority for the European Union and strong measures shall be applied to achieve its targets fixed for Europe as a reduction of 8 % of equivalent CO₂ emission in period 2008 – 2012.

In almost all Eurovent/Cecomaf working groups the issue of energy efficiency has been discussed during the last several years. There is a general agreement that industry must be proactive and propose relevant actions in advance, before some mandatory measures are being decided by the European Commission or National Authorities. That would be the best way to help the industry to meet this important challenge.

The Eurovent WG1 ‘Fans’ has been involved in energy efficiency issues for many years. Fans are basic elements of many if not all air conditioning and refrigerating products. Energy efficiency of a fan depends of several parameters, first of all is the efficiency of the motor. Use of high efficiency electrical motors is the first step in achieving the smallest energy consumption. It is followed by better design of fan and
then by correct installation. System effect is extremely important for fans and several experimental studies were performed.

The WG 6B „Air Conditioners“ has been directly involved in the SAVE project EERAC concerning energy efficiency of room air conditioners. This project was finalised at the end of 1999. Using the data provided by manufacturers and available from Eurovent Directory of Certified Products, it has been realised that energy efficiency of air conditioners presented on the market varies widely: the best units have sometimes two times higher efficiency than the worst.

Two possible policies have been analysed in detail: energy labelling and minimum efficiency.

Energy Labelling as applied with success to many home appliances like domestic refrigerators was an obvious measure. However the labelling itself means only a clear information to buyers – it is expected that buyers will prefer better equipment and that in this way the global, average efficiency of the products sold on the market will increase. Labelling Directive for small Air Conditioners has been prepared by the European Commission and was published in April 2002. The WG 6B took a very active part examining drafts, proposing modifications and clarifications. Although not all comments were accepted the final version is much closer to our wishes than the first draft.

Full mandatory application of this Directive has been fixed for 30 June 2003. However the relevant test standard needed to serve as the reference document was missing; new revised standard EN 14511 covering all products in the scope of the Directive has not been finalised before May 2004. Following several discussions with officials from the European Commission, the Labelling Committee decided to postpone the application till just before the summer 2004.

Mandatory minimum efficiency has been introduced in many countries outside of Europe. This is the simplest way to eliminate low efficiency products from the market but it has a very important effect on the industry and must be applied carefully. In order to avoid such regulation the WG 6B has prepared a proposal on voluntary minimum efficiency to be supported by Eurovent certification. After many discussions the proposal received overwhelming approval from individual manufacturers and national associations.

The first practical action was applied on 1 January 2004 when air conditioners under 12 kW cooling capacity having the lowest classification (class G) were eliminated from the certification programme and, as the certify-all procedure must be applied, from the market.

The effect of these measures can be seen on following diagrammes. Units with lowest efficiency (Class G) were eliminated and the minimum value is now 2.20. Manufacturers are presenting unites with higher efficiency and the average efficiency of all air conditioners is increasing.
EUROVENT CERTIFICATION

Evolution of efficiency of split, non ducted, air-cooled Air conditioners up to 12kW

<table>
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</table>

The next step to eliminate classes F and E has been scheduled to be implemented in 2008. A proposal in connection with the Energy using Product Directive has been prepared by the WG6B in June 2005.

The WG 6A „Chillers“ has been examining the energy efficiency issues for liquid chilling packages – involved products cover capacity range from few kW to several MW.
Several possible actions have been examined. In the certification programme, it was already decided that the energy efficiency (EER and COP) replace the power input as the certified characteristics. A voluntary classification system has been implemented although for such large equipment no physical labels will be fixed. However classes will increase awareness of users that the energy efficiency is an important issue but also the manufacturers when they design new equipment. With a classification it may be easier to eliminate, like for air conditioners, the low efficiency products. The effect on the market has already been identified as some users simplify their request asking Class A products.

The use of chillers and the real annual energy consumption has been largely discussed. As the part load efficiency has a very strong impact on consumption, in the SAVE study EECCAC – Energy Efficiency and Certification of Central Air Conditioners - this issue has been treated exhaustively. This study was initiated by Eurovent/Cecomaf and manufacturers are actively participating. An integrated energy efficiency index called ESEER similar to IPLV (Integrated Part Load Value) developed in the USA and used by ARI, was established for the European conditions. The study was finalised in 2004 and experimental application started in 2005. Part load certification will be implemented in the Eurovent certification in 2006.

The WG 6C „Air Handling Units” after finalising the Life Cycle Cost project has realised that the most important part of this cost is the energy consumption. Although other factors, like maintenance, are also very important, the best means to decrease the life cycle cost of an air handling units is to design and operate in the optimum way with respect to energy consumption. A Eurovent Recommendation concerning assessment of the energy consumption of air handling units has been prepared. This document provides the detailed analysis of all components: fans, cooling and heating coils, heat recovery units. Recommendation was published in May 2005.

The Eurovent WG 4 B „Air Filters „, has found, during the work on Life Cycle Cost project, that energy consumption represents the largest part of the cost. Although the filters are passive elements and do not consume energy directly, the pressure drop they introduce in the flow is related to fan consumption. Selection of filters and their replacement should be made taking into account not only their primary purpose (cleaning the air) but also the possible energy saving. The relevant Eurovent Recommendation concerning calculation of Life cycle Cost of Air Filters was revised in 2004.

The WG 14 „Refrigerated Display Cabinets” has been working on annual energy consumption. The Group has been very much involved in the action undertaken by public authorities in the United Kingdom where Market Transformation Programme is aimed to increase the use of more efficient products. In order to implement the Eurovent Certification as the single data base for all Europe it will be necessary to highlight more efficient display cabinets. In addition, the users need to estimate the cost of annual energy. Conventional formulas have been presented, but more study will be necessary to achieve a valid method.
The energy efficiency appears now everywhere, for almost all products and under different aspects. In standardisation, the valid methods of testing have to be established. The certification will be more and more used not only to check the validity of claimed data but also to remove low efficiency products from the market.

The studies of Life Cycle Cost almost always shows that the energy consumption represent the highest part of this cost; even for passive elements like filters, a small decrease of pressure drop represents a huge economy of energy on the life cycle basis.

Eurovent/Cecomaf continues to show its commitment to energy efficiency improvement and tries to propose practical and easily verifiable measures.
The Role of the Fan Industry in the Field of Energy Efficiency in Motor Driven Systems

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It has often been said (well certainly by me!) that fans are a ‘mature’ product. They have been around, or nearly round, and running most of the time, since at least the 16th century. It was not of course until the beginning of the 19th century that they were motorised with the new fangled steam engine. Now of course 99% of them are driven by electric motors. It may come as some surprise to hear that about 18 to 20% of all the electricity generated in the European Union is consumed by fans. As a product category, this is second only to pumps.

Energy prices rose considerable in the 1970s and 1980s such that attention was directed towards all machinery consuming energy. Even the humble fan, which had escaped undue attention now quivered (or perhaps vibrated?) in the searchlight of efficiency. Just as we were all stirring from our lethargy, energy tariffs stabilised somewhat in the 1990s, possibly resulting from the privatisation of the Electricity generating companies in a number of European countries. Now a resumption of cost increases is apparent due to the rocketing price of oil, whilst a mounting concern for the future of the planet, reinforces the need for energy efficiency. And, of course, we have to face the fact that fossil fuels are a finite resource.

So what are we to do? Undoubtedly there has been a revival of interest in natural ventilation, but this has its limitations. The propulsive force is at its minimum on hot windless days – just when the occupants of a building most demand ventilation. It’s not really acceptable in buildings with large floor areas or in high-rise ‘skyscrapers’. Occupants may prefer access to opening windows – but not if its hot, humid, dusty and noisy outside. The output of office workers, and hence their efficiency, has been shown to reduce when the ambient conditions are outside a defined comfort zone.

So improved efficiency is the way forward. Would it come as a surprise to hear that I believe it should be possible to achieve a reduction across the Union in total fan power input of 30% simply by the better selection of fans, their transmissions, their motors and their controls? Let’s consider each of these items in turn:

a) The fan itself: The last major innovation in fan design was the introduction of the aerofoil bladed centrifugal fan in 1938. This achieved a static efficiency of 84%. In the succeeding years this has been pushed up to about 88%. But out in the wide world we still have thousands of forward curved bladed centrifugal fans which are lucky if they achieve 65%. Indeed the smaller mass-produced sizes with ladder strip impellers often struggle to achieve 50% - but they are cheap! In like manner, axial flow fans, which can reduce system resistance by eliminating bends in the ductwork, are frequently of the Tubeaxial type (i.e., without guide vanes). The rotational energy at the outlet is thrown...
away and **real** efficiency on blowing systems is often moderate. Replacement by, or modification to, the Vaneaxial alternative should give a higher usable efficiency.

**b) The transmission:** Many fans in the HVAC industry are driven through pulleys and vee belts. This gives flexibility to the fan manufacturer who can cover a wide duty range with a limited number of models. The system designer can take comfort in the thought that if his system resistance calculations prove wrong, then a simple pulley change can rectify the situation. But in an age where speed control is becoming de rigueur do we really need such drives? It has to be said that some designers have recognised this and are now specifying coupling drives for centrifugal fans or fan impellers mounted directly on the motor shaft extension. This also overcomes the problems for maintenance engineers. They often specified a minimum of 2 belts on small drives, in the interests of security – even if it did make the drive much less efficient.

Of course the vee belt manufacturers have not stood still. Raw edged belts are much more flexible and can transmit more power at greater efficiency, such that a drive efficiency of 98% is possible. But a coupling drive, or the fan impeller directly mounted on the electric motor shaft is even better.

**c) The motor:** For many years, certainly in the larger sizes, the Squirrel cage induction motor has reigned supreme. It is robust, reliable, requires little maintenance and is relatively cheap. Over the last few years there has been a gradual improvement in its efficiency both at full and partial loads, by the inclusion of greater amounts of active material. All this has been achieved by the motor industry itself without undue pressure from government.

There has also been considerable research conducted into other forms of electric motor. These are especially attractive in the smaller sizes where the induction motor may be only 60% efficient. Thus permanent magnet motors, switched reluctance motors and D.C. motors are becoming available which push this above 80%.

**d) The controls:** Perhaps one Central Government campaign in many countries which has been successful in the last 10 to 15 years has been in the promotion of the inverter. This has given us a relatively cheap form of speed control for the already reliable induction motor. Wherever the resistance of the system is a function of the flowrate squared, it is ideal. Care should however be taken to ensure that this is the case. There are many systems which incorporate a fixed element of pressure e.g., VAV systems. Dependent on the magnitude of this fixed element, speed control may not be so acceptable.

So what have I said about future development in fans? Very little so far. There will of course be any number of new products which claim to be revolutionary, but the reality is that they are frequently exercises in repackaging. The real progress will be made in optimising the package and making better use of the technology already available to us. For the last 40 years the fan industry has been busy making the most competitive i.e., cheapest product. Contracts have been won and lost on a few percent. Now, if the Commission has its way, minimum energy costs should be the criteria. This should be
the sum of the energy expended in making, running, maintaining and disposing. But far the most important of these is the running cost, which often exceeds the capital cost in the first few months of the plant life.

The big problem of course is that the person who buys the fan doesn’t have to pay for the electricity to run it. And so government intervention is inevitable. In the United Kingdom the next editions of the Building Regulations parts F and L give us some clues as to what will happen. Similar regulations are already in place in Sweden, and other countries are considering similar constraints. Just a little mathematics to set the scene:

\[
\text{Power input kW} = \frac{Q \times p}{\eta_F \times \eta_T \times \eta_M \times \eta_C}
\]

Where

- \( Q \) = flowrate m\(^3\)/s
- \( p \) = fan pressure kPa
- \( \eta_F \) = fan efficiency expressed as a decimal
- \( \eta_T \) = transmission efficiency expressed as decimal
- \( \eta_M \) = motor efficiency expressed as decimal
- \( \eta_C \) = controls efficiency expressed as decimal

If we know the duration of time at a specific duty, and the corresponding efficiencies at that duty, we can calculate the kWh and hence the electricity bill. If the electricity generating companies are doing their job properly, this will have a direct relationship with their CO\(_2\) emissions.

Up to this point we have said nothing about the system designer. But he has probably the biggest responsibility of all. Just to encourage him, the new regulations require target levels of Specific Fan Power. There is a Table 5 which gives requirements for various types of plant. As an example, for a system with central mechanical ventilation, heating and cooling the values are: 2.0 for new buildings and 2.5 for refurbished buildings.

Specific Fan Power = kW/m\(^3\)/s (or W/l/s – it’s the same thing)

These of course are summed for the installed power of all the fans in a building for the total flowrate – supply or extract, which ever is the greater.

Rearranging with the previous formula:

\[
\text{Specific Fan Power} = \frac{p}{\eta_F \times \eta_T \times \eta_M \times \eta_C}
\]
Whilst all the component efficiencies are important, of as great or greater importance is the value of the fan pressure i.e., the system resistance. No longer will it be acceptable to ‘guess’ extract systems at 500Pa and the supply air-handling unit at 1500Pa, leaving the balancing company to sort out the mess by adding resistance. That’s throwing away energy! No, resistances will have to be properly calculated and all efforts made to reduce them, by easier or vaned bends, reduced duct velocities, circular cross sections etc, etc.

I am sure that the audit of installed plants, just to see how good they are, and what improvements could be made, will be revealing and rewarding.

Not very exciting, but undoubtedly the future for the fan industry. Certainly companies will continue to expend much time and energy in producing quieter units, to meet that other pollutant – noise, whilst the improved air tightness of buildings will demand more controlled ventilation. But that must not divert us from the prime task – to reduce the energy consumed.
Axial-Flux Solid-Rotor Induction Motor

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Abstract

Axial-flux (AF) electrical machines offer an alternative to conventional radial-flux (RF) machines. Especially, in applications in which the axial length of the machine is a limiting design parameter. In this paper the properties of an AF solid-rotor induction motor are discussed. Also, some other possible realisations of AF induction motors with disk shaped rotors are discussed. The construction proposed in this paper is one rotor – one stator AF machine configuration. The construction was tested by constructing and measuring a prototype of an 11 kW and 7200 rpm AF induction motor. Finally, a comparison between the two dimensional finite element calculation (2D FEM) and test results is presented. In future AF machines might be used on a large scale of applications owing their special features and distinct advantages compared to conventional RF machines.

1 Introduction

Electrical machines may be categorized according to the machine’s conductor geometry and field orientation as:

- Radial-field machine, where the active current carrying conductors are axially positioned, the air-gap field orientation is radial. Usually, a cylindrical rotor rotates inside a stator tube or in some cases, a tubular rotor rotates around a stator.
- Axial-field machine, where the active current carrying conductors are radially positioned and the air-gap flux is axial in direction.
- Linear machine, where the mutually perpendicular flux and the conductors are arranged along a linear path.

The history of electrical machines shows that the first machines were of the axial-field type. Based on the principle of electromagnetic induction, Faraday invented a primitive disc motor in 1821. That motor was built in the form of an AF machine. The machine is commonly known as the Faraday disk. The disadvantage of the machine was the low voltage and high current of the motor. Faraday’s disk machines were soon replaced by radial-field machines (Chan, 1987). The first RF machine was patented by Davenport in 1837 (Atherton, 1984). The Radial-field machines have been and are still dominating excessively the markets of the electrical machines.

One drawback of the single-sided AF motor design is the strong magnetic force between its stator and rotor that acts on a rotor bearing. This problem may be alleviated by using a sandwich configuration. There are two possible ways to realize the sandwich configuration: a stator placed between two rotors or a rotor placed between two
stators. In recent years the developments of new construction techniques have overcome the traditional disadvantages of AF machines. Despite of the success of RF machine the possibility of developing more powerful AF machines have also been under research interest particularly due to special-application-limited geometrical considerations.

2 Potential Applications

AF induction motor offers the solution into applications in which the axial length of the machine is a limiting design parameter. In certain applications the AF motor requires less material than radial motor does for the same operation. Polard (1979) shows in his theoretical considerations that the axial air-gap motor needs 13-14 percent less copper and 21.5-32.5 percent less iron than similar traditional motors producing equal power. On the contrary, Parviainen (Parviainen, 2005) showed that to reach the same efficiency the AF machine needs usually more copper than the RF machine. AF machines possess special properties, which have distinct advantages in certain applications, particularly in those applications where the axial-field machine can be integrated with the driven machine. A disk type induction machine promises also high utilization of the active material and thus favourable power density. (Kubzdela, 1988) Generally, the AF induction motor seems to be a motor type that suits well to be integrated in some types of driven machines.

Despite of the advantages and many application possibilities induction motors with disk rotors are rather rare in production. Some potential applications are:

- One of the principal features of AF induction motor is the small inertia that is achieved by using of an ironless rotor. The possibility of using an ironless rotor in the AF machines makes it suitable for servo and, in some cases, even high-speed applications. (Hall, 1976)
- Because of the relatively flat shape of the AF machine, it is suitable for use to drive fans, wheels, pumps and domestic appliances. (Corbet, 1976)
- Because of its better power-to-weight ratio the AF machine is suitable for use in electric vehicles. (Evans, 1980)

3 Classification of Axial-Field Machines

In theory, each type of RF machine will have a corresponding AF machine. The magnetic circuit and the number of air-gaps in an axial-field machine can readily be varied. An AF machine can be constructed in one on the followings ways: (Chan, 1987)

- single stator and single rotor (one air-gap),
- single stator sandwiched between two rotors (double air-gaps),
- single rotor, sandwiched between two stators (double air-gaps),
- a variety of multiple stators and rotors (multiple air-gaps)
Figure 1 shows the topologies of the magnetic circuits of different AF machines.

Figure 1: Magnetic circuits of AF motors ($\phi$ is the flux). a) Single air-gap, b) double air-gaps, centre element with yoke and c) double air-gaps, yokeless or coreless armature

3.1 Construction of the Axial-Flux Induction Machine

Several possible realizations of AF induction machines are reported in figure 2. (Bramanti, 1978) Figures 2 a) and b) show a one-stator machine with an iron and a mixed aluminium-iron rotor. In these cases the axial force between the stator and the rotor may play a negative role. The realisation shown in figure 2 c) reduces the axial force to a practical minimum.

The single-rotor – single-stator structures shown in figures 2 a) and b) are simple AF solid-rotor induction motor configurations. The disadvantage of these structures is the axial force between the rotor and the stator as a consequence of which more complex bearing arrangements and a thicker rotor disk are needed. This is valid compared to the structure in which the axial forces are balanced.

Figure 2: AF induction motor configurations: a) single stator and an iron rotor, b) single stator and a mixed aluminium-iron rotor and c) double stator and an aluminium rotor. (Aho, Valtonen, 2004)
In the past, the basic layout of AF induction motors comprised of two facing stators and a disk shaped rotor in the gap between the stators. Rotors were typically fabricated of a low resistivity material such as copper or aluminium, which caused lack of structural rigidity in the rotor. To reach large enough current carrying surface the thickness of such a rotor must have a considerable value. Two air-gaps and a thick rotor disk cause a low power factor. Some disk shaped rotors were thus designed wherein small portions of the rotor were fabricated of some ferromagnetic material. Some rotor disks had axially oriented iron strands in the rotor to carry the magnetic flux. (Fernando, 1998) In these designs, the ferromagnetic material was used to enhance the flux carrying capacity of the rotor. The ferromagnetic material portion and the axially oriented iron strands do not increase the current carrying capacity of the rotor.

In view of these known induction motor designs, the AF induction motor that enhances both the flux carrying capacity of the rotor and the electrical conductance of the rotor in order to achieve high torque and high efficiency was manufactured.

### 3.2 Construction of the Prototype

The motor studied is designed in the Department of Electrical Engineering at Lappeenranta University of Technology. The structure of the AF solid-rotor induction motor considered in this paper is depicted in figure 3.

The structure of the prototype consists of a single squirrel cage rotor and a single stator. The rotor of the motor was built using normal construction steel Fe-52 having saturation flux density 2.1 T. The resistivity of the rotor core material @ 20 °C is 26.0 μΩcm and the aluminium 3.5 μΩcm. The stator was made of laminated magnetic steel M270-50A. The rated motor values are listed in table 1.

![Figure 3: A single-sided disk induction motor structure. The solid rotor is equipped also with aluminium current conductors](image-url)
Table 1: Rated motor values

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power $P$</td>
<td>11.0</td>
<td>kW</td>
</tr>
<tr>
<td>Torque $T$</td>
<td>16.8</td>
<td>Nm</td>
</tr>
<tr>
<td>Voltage $U$</td>
<td>400 V</td>
<td></td>
</tr>
<tr>
<td>pole-pair number $p$</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Frequency $f$</td>
<td>244</td>
<td>Hz</td>
</tr>
<tr>
<td>Efficiency $\eta$</td>
<td>0.9</td>
<td></td>
</tr>
<tr>
<td>Power factor $\cos \phi$</td>
<td>0.65</td>
<td></td>
</tr>
<tr>
<td>Nominal slip $s$</td>
<td>1.6</td>
<td>%</td>
</tr>
</tbody>
</table>

In Table 2 the main dimensions of the motor are shown.

Table 2: Motor dimension

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stator core length $L$</td>
<td>90.5</td>
<td>mm</td>
</tr>
<tr>
<td>Stator outer diameter $D_{out}$</td>
<td>194.0</td>
<td>mm</td>
</tr>
<tr>
<td>Stator inner diameter $D_{in}$</td>
<td>124.0</td>
<td>mm</td>
</tr>
<tr>
<td>Air-gap length $\delta$</td>
<td>1.2</td>
<td>mm</td>
</tr>
</tbody>
</table>

4 FEM Model and Measurements of the Prototype

A disk rotor induction motor requires three-dimensional time stepping calculation, which is extremely tedious and very time consuming. Also, the solution of the complete, three-dimensional magnetic field of an induction motor is still too demanding a problem for present day computers. That is why in this paper the geometry of the machine is transformed to normal RF geometry and two-dimensional FEM is used in the analysis. To reduce the 3D-problem to a 2D-problem, the motor is cut through the mean radius of stator. The main hypothesis adopted, is cutting the motor through its mean radius that makes it possible to transform the actual toroidal form into a planar one. (Abdollahi, 2004)

The three dimensional end-region fields of the stator are modelled approximately by using constant end-winding impedances in the circuit equations of the windings. The laminated stator core is modelled as a non-conducting, magnetically non-linear medium. The rotor steel is treated as a conducting, magnetically non-linear material.
The time variation of the magnetic field in an electrical machine is practically never sinusoidal. The non-linearity of iron and the rotation of the rotor require the use of a time-stepping method to accurately solve the magnetic field. However, according to Arkkio (Arkkio, 1987) the torques obtained with the time-harmonic method are very close to the values obtained with the time-stepping method when the slip is smaller than 10%. Because of the slowness of the time stepping calculation and the small nominal slip \( s = 1.6 \% \) of the prototype the time harmonic calculation is used. However, torque ripple and power loss of the rotor were evaluated with the time-stepping transient calculation.

### 4.1 Results of FEM Calculation

Figure 4 shows a calculated torque versus the slip of the rotor. The measured curve and the curve that is calculated with analytical methods are also drawn in the figure.

![Figure 4: Measured and calculated torque versus slip](image)

The time-stepping finite element analysis (FEA) was used to define the torque as a function of time is given in figure 5. The analysis of the torque is based on the numerical solution. The transient calculation was set up by specifying the slip value \( s = 1.6 \% \).
Figure 5: The time-stepping calculation result variation of the electromagnetic torque at nominal rotor speed. The torque settles to the rated value of 16.8 Nm after the initial transients have attenuated. The motor produces a smooth torque.

According to the analytical calculation the nominal torque should be 16.8 Nm as is shown in table 1. Prior to the load test, the nominal slip 1.6% gives a lower torque than it was expected. That is because, the complicated geometry of the prototype and the nonlinearity due to the saturation of the iron core make the analytical calculation of a prototype only approximately. Anyway, comparing the results obtained in figure 4, the FEM method gives higher values than is expected. That, probably, indicates that the rotor radius should be selected more carefully in the 2D calculations to produce the correct torque for the rotor.

The loss components of the prototype can be summarized as copper losses $P_{Cu}$, stator iron losses and rotor eddy current losses $P_{Fe}$ and mechanical losses $P_{f}$ (losses of the bearing and the blower). Losses of the prototype at the nominal point are shown in the table 3.

Table 3: Losses of the prototype at the nominal point

<table>
<thead>
<tr>
<th>$P_f$ [W]</th>
<th>$P_{Fe}$ [W]</th>
<th>$P_{Cu}$ [W]</th>
<th>$P_{tot}$ [W]</th>
</tr>
</thead>
<tbody>
<tr>
<td>220</td>
<td>823</td>
<td>277</td>
<td>1320</td>
</tr>
</tbody>
</table>

The harmonic deviations in the air-gap magnetomotive force (mmf) wave cause losses especially in the solid steel parts of the motor, since these harmonic waves penetrate into the conducting material and cause eddy currents, which produce ohmic losses in the steel. The time-stepping FEA was used to define the power losses of the rotor. The power loss calculation versus time is shown in figure 6.
4.2 Results of the Measurements

Figure 7 shows the measured efficiency of the motor as a function of the load torque.

Figure 7 proves that the calculated efficiency given in table 1 corresponds to the measured values. Figure 8 shows the behaviour of the motor power, fundamental wave power factor and torque.
Figure 8: Load graph

Figure 8 shows that the fundamental power factor is smaller than was expected in table 1. The lower value may depend on the difficulty to evaluate the solid rotor core material behaviour in the 2D calculations.

## 5 Conclusion

The modelling of AF machines is determined by contradictory requirements related to the fastness and accuracy of the computations. From the modelling point of view, an AF machine has a 3D geometry. Therefore, using an analytical design method or the 2D FEA, which both are usually to be performed on the average radius of the machine, does not generally yield sufficiently accurate computation results as can be noticed from figure 4. With the 3D FEA, it is possible to take into consideration the actual 3D structure of the machine, but performing the computations is often too time-consuming. (Parviainen, 2005)

A good alternative for the construction of the rotor disk is to use a solid rotor core, which is fabricated of ferromagnetic steel. As conductors in the rotor an aluminium cage may be used. This type of a rotor provides sufficient structural integrity for the rotor and the bars embedded in the rotor enhance the electrical conductance of the solid rotor and improve thus the motor energy efficiency remarkably.

It is also possible to fabricate the bulk of the rotor disk from axially slitted solid steel. In this case the torque of the motor is lower than the torque of the AF squirrel cage solid rotor induction motor. Therefore, an improvement design with reduced rotor resistance was achieved by embedding of conduction strips in the rotor. The conduction bars can be fabricated from a high conductivity material such as copper or aluminium.
Some special features can be found of the AF machine, which distinguishes it from conventional radial-field machine. Their main advantages over the conventional machines are: AF machine can be designed to possess a higher power-to-weight ratio, usually the AF machine has a larger diameter-to-length ratio, AF machine has a planar and adjustable air-gap. The topology of the magnetic circuit of the AF machine can be varied. Because of these advantages axial-field machines are particularly suitable for applications where their properties offer distinct advantages over their conventional machine counterparts. (Chan, 1987)

6 References


The Effect of Inter-bar Current on Induction Motor Losses

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Abstract

In an ideal induction motor rotor current flows only in the rotor cage. In practice cages are never perfectly insulated, and current also flows from the bars into the laminated core. In recent years, motor manufacturers have been investigating the efficacy of certain techniques for creating an insulating layer between the bars and the iron core. Measurements made in Manchester on a range of nominally-identical rotors that had been subjected to a range of treatments by their manufacturer showed that the bar-to-iron contact resistance could be increased by three orders of magnitude by appropriate treatment. This was found to have a significant effect on the performance of the single-phase machines to which the test rotors belonged. In this paper we use the practical results of the previous study, together with a new model for inter-bar currents that arose from that study, to explore the potential benefits that bar insulation would have on the losses in industrial three-phase motors.

1 Introduction

Inter-bar currents are known to produce additional rotor losses. Continued efforts to increase motor efficiency by better design, rather than by simply increasing the quantities of active materials, have lead to renewed attempts to quantify these additional losses (Williamson and Smith 2002, Dorrell et al. 2003, Carlson et al. 2003, Serrano-Iribarnegary et al. 2005). This will allow the cost of the possible means for their reduction to be weighed against an analysis of the benefit that such reduction will bring.

One of the difficulties associated with modeling inter-bar currents is that their magnitude does not simply depend on the design of the machine. They are strongly influenced by the manufacturing process by which each individual cage rotor is fabricated. All other factors being equal, the key parameter that governs the flow of inter-bar currents is the contact resistance between the bars of the cage and the iron core of the rotor. This parameter has been found to exhibit a high degree of randomness. Nominally identical rotors from the same batch, which should have therefore been through the same manufacturing processes, have been found experimentally to have mean bar-to-iron contact resistances that can differ by one or more orders of magnitude. This randomness is further compounded by the fact that even in a single rotor the contact resistance will vary significantly not only from bar to bar but also with axial position along the length of any particular bar. It is little wonder that the best advice that can be given to manufacturers is that they should quantify their own manufacturing processes (by making measurements on a sample of rotors for each of their rotor designs) and that quenching does indeed increase the contact resistance.
Despite the difficulties stated above, a succession of authors have attempted to develop analytical models which are capable of allowing for the flow of inter-bar currents, albeit in an idealized machine in which the bar-to-iron contact resistance is uniform over the entire rotor cage. The first noteworthy treatment of this phenomenon was provided by Rossmaier in 1939, who proposed a model that was subsequently improved and developed through the work of a succession of authors (Odok 1958, Christofides 1956, Weppler 1966, Subba Rao and Butler 1969, and Williamson and Smith 2002). A defining feature of Rossmaier’s model, which is shown in figure 1, is that the inter-bar currents are considered to flow only between adjacent pairs of bars.

![Rossmaier's model for inter-bar current flow](image)

Figure 1: Rossmaier’s model for inter-bar current flow

This model has been challenged as physically unrealistic (Watterson et al. 1989, Serrano-Iribarnegary et al. 2005) on the grounds that once current has passed from the cage into the rotor core, it is able to flow around the core through the low-resistance iron laminations to rejoin the cage at any other rotor bar. Such considerations have led to the proposition of an alternative model, shown in figure 2 (Poh, C.Y., 2004; Williamson et al., 2005). This new model has now been verified experimentally using an extensive set of measurements made on a large sample of nominally-identical 28-slot cage rotors from a 2.5HP (1865W), 60HZ, 2-pole permanent-split capacitor motor.

These rotors were provided by their manufacturer in batches of six. All of the rotors in each batch had been through the same sequence of processes during manufacture. There were nine distinct batches, each featuring one or more particular manufacturing procedure intended to increase bar-to-iron contact resistance, giving a total of 54 rotors. Prior to shipping, the manufacturer carried out standard performance tests on every rotor, using the same single-phase stator to eliminate any variations due to stator differences. After arrival in Manchester their end-rings were machined off, and the resistance between all adjacent pairs of bars carefully measured to obtain the mean bar-
to-iron resistance for each rotor (Williamson et al., 2004). These measurements revealed that the various range of treatments used by the manufacturer had produced rotors with mean bar-to-iron resistances that ranged over three orders of magnitude.

Figure 2: Inter-bar current model with current flow to core

The starting torque divided by the square of the input current is a performance parameter that is sensitive to inter-bar current flow, and which was readily calculated from the industrially measured performance characteristics. Figure 3 compares these experimentally-determined values of $T/I^2$ versus the measured bar-to-bar resistance for three inter-bar current flow models. Model A is Rossmaier’s model. Model B is the model of figure 2, with an allowance for the resistance of the rotor core. Model C is also the model of figure 2, with the resistance of the rotor core neglected.

In view of the non-uniform nature of the bar-to-iron contact resistance, which has already been commented upon earlier in this paper, the correlation evident in fig 3 between measurement and calculation is remarkable. Moreover, the results presented in figure 3 demonstrate quite clearly that the new bar-to-core flow model is superior to Rossmaier’s bar-to-bar model. They also suggest that the resistance of the rotor core to inter-bar current flow can be neglected, even at very low bar-to-bar resistances.
The inter-bar current in figure 1 is driven by the voltage difference between the two adjacent bars. If the voltage at one point in a bar is $V$, then the corresponding point in the next bar is at the same voltage, with a phase shift that depends on the number of poles and the number of bars. The voltage driving the inter-bar current is given by

$$V_{bb} = V \sin \left( \frac{\pi p}{N_b} \right)$$

(1)

$p$ is the pole-pair number, and $N_b$ is the number of rotor bars. Generally rotors have several bars per pole so that the sine term is small. For the rotors used in the tests, for example, $N_b = 28$, so that for the fundamental two-pole field, $V_{bb} = 0.11V$. By contrast, the inter-bar current in figure 2 is driven by the voltage between the bar and the rotor core, which, if the resistance of the core itself can be neglected, acts as a virtual earth. The voltage which drives the inter-bar current is now given, on the same basis as above, by

$$V_{bb} = V$$

(2)

Comparison between equations 1 and 2 reveals two important differences between Rossmaier’s model and the new model. The sine term in equation 1 both attenuates the voltage which drives the inter-bar current and implies that the flow of such current is favoured by a low number of rotor bars per pole. This has led the present authors to conclude erroneously that the additional joule loss produced by inter-bar currents is predominantly due to the higher harmonic field distributions within the machine (Williamson and Smith, 2002).

In this paper we re-examine the effect that inter-bar currents have on the losses in three-phase cage motors, using the new bar-to-core model. Our purpose is to provide...
motor manufacturers with information that will help them make sound decisions on the benefits of insulating their rotor cages.

2 Additional Joule Losses in Industrial Three-phase Machines

In this section we use the bar-to-core current flow model to examine the additional joule losses produced by inter-bar currents in a range of three-phase cage machines.

2.1 1.1kw 4-pole machine

Figure 4 shows the variation of full-load joule loss with bar-to-bar resistance for a 1.1kW, 400V, 4-pole machine in a D90 frame. This machine has 36 stator and 32 rotor slots. The rotor of is normally skewed by one rotor bar, equivalent to 1.125 stator slots, or 22.5 electrical degrees. The nominal full-load efficiency is 79.8%, indicating a total loss of around 280W. Figure 4 also includes the variation of copper loss for an unskewed version of the same rotor.

The curve for the skewed machine shows that as the bar-to-bar resistance falls the copper losses increase from around 216.4W (insulated cage) to peak of approximately
220.8W, an increase of about 4.4W. This is approximately 1.5% of the total full-load loss. If the bar-to-bar falls even further the joule loss begins to fall, and at very low values the loss will be lower than that with an insulated cage. The explanation for this is straightforward. The current flow path through the laminations parallels that through the end-rings. At such low values of contact resistance an proportion of end-ring current is diverted through the rotor core. The droop in the characteristic is the result of a lowering of the effective end-ring resistance by this parallel path. This is evidenced by the curve for the joule loss when the machine has an unskewed rotor. It may be shown that inter-bar currents do not flow in an unskewed rotor with zero impedance end-rings. The characteristic for the unskewed machine shows no variation of joule loss with bar-to-bar resistance at high resistance values. The losses fall, however, at low bar-to-bar resistance as the parallel path through the laminations begins to divert current from the end-rings at either end of the machine. It will be noted that the droop in the characteristic begins at approximately the same value of bar-to-bar resistance ($10^{-5}$ Ω-m) as the peak in the characteristic for the skewed machine. The authors have previously commented that at extremely low values of bar-to-bar resistance the inter-bar currents effectively ‘undo’ the rotor skew (Williamson and Smith, 2002). This is again evident in Figure 4, which shows that at the lowest values of resistance the curves for the skewed and unskewed machines converge. However, it should also be noted that the rotors used to obtain the practical results given in Figure 3 were of roughly the same physical size as that of this 1.1kW machine, and the lowest bar-to-bar resistance measured on those rotors was close to $10^{-5}$ Ω-m. It may therefore be expected that in practice the 1.1kW machine will be operating at a point somewhere to the right of the peak in Fig 4.

### 2.2 7.5kW 4-pole machine

Figure 5 shows the variation of full-load joule loss with bar-to-bar resistance for a 7.5kW, 400V, 4-pole machine in a D132 frame. This machine has 36 stator and 28 rotor slots. The rotor is normally skewed by 1.15 rotor bars, equivalent to 1.5 stator slots or 30 electrical degrees. The nominal full-load efficiency is 88.6%, indicating a total loss of around 970W. Figure 5 also includes the variation of copper loss for the same machine with an unskewed rotor. The curves in Figure 5 are very similar to those of Figure 4, showing a peak loss of 693W compared to 646W for an insulated cage, a difference of 4.8% in the total loss. In this instance the peak joule loss occurs at bar-to-bar resistances around 10 times higher than in the 1.1kW machine, a consequence of their relative sizes.
The Effect of Inter-bar Current on Induction Motor Losses

2.3 7.5kW 2-pole machine

Figure 6 shows the variation of full-load joule loss with bar-to-bar resistance for a 7.5kW, 400V, 2-pole machine in a D132 frame. Like the 4-pole machine in the previous section, this machine also has 36 stator and 28 rotor slots, with a rotor skewed by 0.78 rotor bars, equivalent to 1.0 stator slot, or 10 electrical degrees. Its nominal full-load efficiency is also 88.6%, giving the same total loss of 970W. The figure includes the variation of copper loss for the same rotor, without skew.

The curves in Figure 6 suggest that inter-bar currents may add as much as 19W to the joule loss, equivalent to 2.0% of the total loss. In two-pole machines the end-rings make a proportionally higher contribution to the overall resistance of the cage than they do in machines with higher pole numbers. As a consequence the parallel path through the rotor laminations becomes evident in Figure 6 at higher values of bar-to-bar resistance than in Figure 5. Comparison between these two figures also shows that at high values of bar-to-bar resistance, rotor skew in the 2-pole machine does not increase joule loss, whereas in the 4-pole machine it increases it by around 21W. This is because in the 2-pole machine the skew is only 10 degrees, whilst in the 4-pole it is 30 electrical degrees, giving skew factors of 0.9987 and 0.9886 respectively.
2.4 75kW 4-pole machine

Figure 7 shows the variation of full-load joule loss with bar-to-bar resistance for a 75kW, 400V, 4-pole machine in a D250 frame. This machine has 48 stator and 40 rotor slots. The rotor is skewed by 0.075 rotor bars, equivalent to 0.0625 stator slots, or 0.9 electrical degree. The characteristics for the skewed and unskewed machines are superimposed in Figure 7, a consequence of the rotor skew being very small. This is typical of the rotors of larger machines, the rotors of which are often unskewed. As a consequence the joule loss is relatively insensitive to bar-to-bar resistance except at extremely low values, for the reasons already discussed.
3 Conclusions

The results presented in Figures 4-7 show that the relationship between bar-to-bar resistance and joule loss is complex, depending upon several machine parameters. Principal amongst these are the rotor skew, the end-ring impedance, and the pole number.

As a rule, increasing the rotor skew increases the joule loss, which for realistic values of bar-to-bar resistance is further increased as the contact resistance between the rotor bars and the lamination iron falls. The corollary to this statement is that the joule loss in an unskewed machine is never higher than that in the same machine with zero skew, a proposition that the authors were able to confirm by carrying out numerical experiments on the machines used for illustrative purposes in this paper.

The rotors of small machines are usually skewed, whilst those of large machines are invariably not. The use of skew brings other benefits, which should clearly be balanced against the possible efficiency gain that would arise from using an unskewed rotor. In order to carry out a realistic assessment of the benefits of either insulating the rotor cage or taking out the rotor skew, manufacturers should first characterise their manufacturing processes by measuring the bar-to-bar resistance on a statistically significant sample of each rotor design they rotor design in their catalogue.
4 References


Abstract

Modern power converters utilize Pulse-Width Modulation (PWM) voltage control. Output voltage high frequency harmonics induce additional electrical machine loss. As there is no accepted PWM loss theory, PWM loss is usually accounted for by machine power de-rating. In-depth understanding of PWM loss mechanisms is important for predicting losses and improving energy efficiency of electrical machines. In this paper we suggest a new time domain PWM loss approach. It assumes that PWM eddy current iron loss dominates over PWM copper and hysteresis iron losses and comprises theoretical normalized PWM loss evaluation and experimental characterization. Once maximal PWM loss is measured, it can be scaled for an arbitrary operating point using simple formula. Theoretical results are shown to be in a good agreement with a published experimental data.

1 Introduction

Understanding different loss mechanisms is important in the general context of improving electrical machine efficiency and, in particular, for correct modeling and reducing losses for energy efficiency sensitive applications like electric vehicle, sustainable energy etc. PWM voltage control of electrical machines causes additional losses compared with linear (pure DC or AC) voltage supply [1]. For AC motor inverter operation, suggested rule of thumb is 20% motor power derating due to PWM loss [2]. Induction motor PWM loss separation experiment showed possible 3 times and more motor iron loss increase for a certain operating point compared with a pure sinusoidal supply [3]. It is somewhat strange that there is no accepted PWM loss theory so far. There are some common wide-spread misunderstandings instead. The first misconception is that PWM loss is mainly due to winding resistive loss. Being true for ironless machines, this statement is incorrect for iron machines that are in the scope of this paper.

Another misconception is about PWM loss dependence on switching frequency. Some people erroneously assume that PWM loss increases with switching frequency increase extrapolating main flux induced PWM loss frequency dependence. Other expect PWM loss reduction following current ripple decrease. We will show that a reasonable approximation is PWM loss independent of switching frequency. Experiments show [3] that twice switching frequency increase practically causes no change in PWM loss.

Our PWM loss engineering approach assumes that PWM eddy current iron loss dominates over additional PWM copper and hysteresis iron losses. It comprises theoretical normalized PWM loss evaluation and experimental PWM loss characterization.

We recommend characterizing PWM loss under maximal PWM loss conditions. Once maximal PWM loss is measured, it could be easily scaled for an arbitrary operating...
conditions using simple formula of PWM core eddy current loss envelope to provide PWM loss upper bound.

In this paper we evaluate PWM loss in DC brush and two- and three-phase AC brushless permanent magnet and induction machines.

2 Major Assumptions Formulation and Discussion

A1. DC bus voltage is constant and semiconductor voltage drops are negligible. Semiconductor switching times are negligible compared with PWM period.

A2. Motor winding time constant is essentially larger than PWM period. Core eddy current reaction can be neglected and eddy current path time constant is significantly lower than PWM period.

A3. Machine magnetic circuits are considered linear, magnetic saturation is neglected.

A4. PWM eddy current core loss is a dominating PWM loss mechanism.

Assumption A1 – ideally stiff DC voltage supply - significantly simplifies time domain analysis. As we will show, under the assumptions A2, A3 elementary local eddy current time distribution is proportional to respective voltage pulsation.

In connection with A3, for AC machine PWM loss on average is not correlated with a main flux induced rotational loss and may be considered independently.

Our approach will be to find normalized PWM loss and then quantify it using PWM loss characterization / separation experiment. We first calculate motor winding PWM voltage pulsation that represents in a proper scale a local core eddy current time distribution. For a multi-phase machine, local eddy current is a superposition of currents produced by different phase windings.

Given a local core eddy current distribution, average eddy current PWM loss is calculated by averaging eddy current square multiplied by core resistance factor on PWM period. For AC machine, eddy current PWM loss after averaging on PWM period is a function of electrical angle and must be further averaged on AC fundamental period.

Suppose we obtained a total normalized PWM eddy current loss. The next stage is to perform a PWM loss characterization experiment. We recommend to measure maximal PWM loss (that includes maximal PWM core hysteresis loss and PWM winding resistive loss). When scaling maximal PWM loss for an arbitrary operating point using PWM eddy current loss envelope, we get an upper bound of overall machine PWM loss.

The above assumptions may be relaxed using coupled field and circuit numerical analysis.


3 PWM Loss in a Solenoid

Consider first the following simple and representative example that gives an illustration to our basic ideas – PWM core eddy current loss for a solenoid controlled by converter with an H-bridge topology (Figure 1). Core magnetic field distribution is considered plane-parallel. While the exact core lamination geometry and physical properties are essential for total loss, they are of no importance for normalized loss consideration.

![Figure 1: H-Bridge Converter with PWM Voltage Control](image)

Instantaneous normalized PWM voltage on one PWM period is shown on Figure 2,a. An average normalized voltage $D$, equal to PWM duty cycle, defines average current $I_{AV}$ (main electromagnetic process). Zero mean voltage pulsation (Figure 2,b) - instantaneous voltage reduced by its average value - is responsible for current ripple and PWM loss.

![Figure 2: Instantaneous Voltage (a) and Voltage Pulsation (b) on PWM Period](image)

Instantaneous current ripple is proportional to time integral of voltage pulsation. Elementary voltage induced in local core eddy current path is proportional to core flux (cur-
rent) derivative. Due to integration and differentiation cancellation, local core eddy current time distribution is proportional to voltage pulsation (Figure 2,b).

As voltage pulsation is defined by an average output voltage, we shall formulate our results — normalized average PWM loss — in terms of converter output voltage.

If switching frequency is increased twice (Figure 3,a,b), PWM current ripple is reduced in the same proportion. However, local eddy current shaping is the same meaning the same PWM core eddy current loss. This will hold with frequency increase until local eddy current finite rise / fall times due to eddy current path finite time constant (inductance) can not any more be neglected compared with PWM period. This is expected to take place at switching frequencies of some hundred KHz while typical switching frequencies of modern servo amplifiers and inverters are in the range of 20-60 KHz.

\[
P_v = \frac{T_t}{0} (1 - D)^2 D + (-D)^2 (1 - D) = D(1 - D). \quad (1)
\]

It has maximum of 0.25 at \( D = 0.5 \) (maximal current ripple point) and can be further normalized for maximum unity

\[
P_E = 4D(1 - D). \quad (2)
\]

Our next step will be to estimate normalized PWM copper resistive and core hysteresis loss and further normalize them for maximum unity. Integrating and normalizing squared piece-wise linear current ripple gives

\[
P_c = 16D^2 (1 - D)^2. \quad (3)
\]

Estimating PWM hysteresis core loss according to local hysteresis loop area as proportional to squared fundamental switching frequency harmonic amplitude gives

\[
P_H = SIN^2 (\pi D). \quad (4)
\]

Figure 3: Voltage Pulsation and Current Ripple for Switching Frequency Increase
While eddy current loss is switching frequency independent under our assumptions, copper loss is inversely proportional to squared switching frequency, hysteresis loss – to switching frequency.

These three kinds of PWM losses are compared on Figure 4. The conclusion is that once overall PWM loss is measured for the maximum loss (maximum current ripple) point $D = 0.5$, using eddy current envelope introduces certain conservatism and delivers an upper bound for overall PWM loss for other operating conditions.

![Normalized PWM Loss Comparison](image)

**Figure 4**: Normalized PWM Eddy Current, Copper and Hysteresis Loss Comparison

## 4 PWM Loss in Permanent Magnet Machines

For permanent magnet machines, PWM eddy current loss is supposed to take place mostly in PWM excited armature yoke because of relatively large equivalent air gap. PWM loss is also expected in permanent magnet alloy materials that, as opposed to ferrites, have relatively high conductivity.

For practical PWM current ripples of 20-30% of rated current, copper loss increase due to PWM even accounting for skin-effect is estimated as 10-15% that alone can’t explain significant total PWM loss. It means that PWM core loss is a dominating mechanism.

### 4.1 DC Brushed Motor

Since there is only one excitation winding, actual rotor core flux distribution is of no importance for normalized PWM loss consideration. Therefore, equation (2) and Figure 4 obtained for a solenoid with DC excitation are applicable to DC motor as well.
4.2 Two-Phase Permanent Magnet AC Motor

For multi-phase machine, total local eddy current is obtained by superposition of local currents induced by different phase windings. Sinusoidal currents of both windings are supplied by separate H-bridge power converters (see Figure 1 where $E$ may be viewed as motor phase back EMF). Motor end effects are neglected. We assume sinusoidally distributed orthogonal motor windings (the results for concentrated windings are the same). For sinusoidal modulation, PWM duty cycle is a sinusoidal function of rotor angle (or time for constant speed). We assume steady state operation and formulate results in terms of normalized phase voltage amplitude equal to maximal duty cycle.

To get a total local core eddy current time distribution, one has to add two phase voltage pulsations weighted by proper periodical angle functions and some core radius functions different for tangential and radial eddy currents. The expressions for radial and tangential core eddy current time distributions are similar.

While squaring and averaging total eddy current distribution, we find that due to orthogonality there is no correlation between PWM losses induced by different windings. Therefore, after time averaging on PWM period and space averaging normalized core eddy current loss – both tangential and radial – is

$$P(\phi) = 0.5[D_{\text{MAX}} \sin \phi (1 - D_{\text{MAX}} \sin \phi) + D_{\text{MAX}} \cos \phi (1 - D_{\text{MAX}} \cos \phi)], \quad (4)$$

$D_{\text{MAX}}$ - maximal duty cycle equal to normalized maximal phase voltage; $\phi$ - phase voltage electrical angle. In (4) we used (1) with a duty cycle that is a sinusoidal function of the angle.

After averaging on electrical rotation (practically, on 45 el.deg interval)

$$P = \frac{2}{\pi} D_{\text{MAX}} - 0.5 D_{\text{MAX}}^2 \quad (5)$$

and after normalizing for maximum unity at $D_{\text{MAX}} = 2 / \pi = 0.637$ (Figure 5)

$$P_E = \pi D_{\text{MAX}} - \frac{\pi^2}{4} D_{\text{MAX}}^2 = 3.14 D_{\text{MAX}} - 2.47 D_{\text{MAX}}^2 \quad (6)$$
4.3 Three-Phase AC Permanent Magnet Motor

Just as for two-phase machine, for a three-phase one normalized PWM eddy current loss is the same for both concentrated and distributed windings. For distributed windings, to get a total local core eddy current time distribution one has to add different phase voltage pulsations weighted by proper periodical angle functions and some core radius functions different for tangential and radial currents. After straightforward but somewhat tedious calculations it comes out that normalized PWM eddy current loss expression (6) (Figure 5) derived for a two-phase machine is valid for a three-phase machine as well:

\[ P_E = 3.14v_A - 2.47v_A^2, \quad (7) \]

\[ v_A = 0.577V_A / V_{DC} \] - normalized fundamental phase voltage amplitude for a star-connected motor; \[ v_A = V_A / V_{DC} \] - the same for a delta-connected one.

This result could be anticipated as a consequence of general equivalence principle for two- and three-phase machines.

5 PWM Loss in Induction Motors

In the first approximation, consider only fundamental magnetic field component and neglect end effects. Suppose toothless stator and rotor cores and both stator and rotor windings representation as equivalent sinusoidally distributed current layers. For high switching frequency, rotor winding may be considered superconducting. At first, we conclude that despite relatively small air gap there is no PWM loss in rotor core because it is effectively shielded by rotor winding.
Secondly, suppose for a moment that comparable AC permanent magnet and induction motors have the same stator - core and winding – and are supplied by the same PWM voltage. PWM current ripple in induction motor stator winding is higher due to rotor winding transformer short-circuit effect (transient reactance). PWM copper loss in induction motor is higher because of increased stator current ripple and PWM copper loss in rotor winding. However, no major increase of PWM stator core eddy current and hysteresis loss is anticipated compared with a permanent magnet motor. This is because stator current ripple increase influence on core ripple flux is exactly compensated by a corresponding current ripple induced in rotor winding that has an opposite phase. The above statement can be proved strictly for infinitely thin infinitely long superconducting stator and rotor windings model.

Therefore, normalized stator core PWM eddy current loss in induction machine may be calculated using (7) and Figure 5.

6 PWM Loss Characterization Experiment

So far we considered normalized PWM loss. Given a DC bus voltage, we suggest to quantify PWM loss by running characterization experiment at maximum PWM loss point and further using PWM eddy current loss envelope to obtain total PWM loss upper bound for arbitrary operation conditions. For different DC busses, total PWM loss is scaled as a squared DC bus voltage. If serial chokes are used, total PWM loss is scaled as inverse squared total equivalent phase inductance.

6.1 PWM Loss Experiment for Permanent Magnet Machines

For permanent motors, we suggest to carry out PWM loss characterization by running a no-load electromagnetic experiment at maximum PWM loss point.

6.1.1 PWM Loss Experiment for DC Brushed Motor

DC motor must be back driven by a prime mover with such a speed that motor back EMF equals half a DC bus voltage \( E = K \omega = 0.5V_{DC} \). PWM amplifier that is run with a zero current command (no-load) will compensate on average for back EMF and deliver \( D = 0.5 \) meaning maximum PWM loss (Figure 4). The power into the motor \( P_{MAX} \) is a total PWM loss if commutator loss is neglected. Using PWM eddy current approximation (2) to get an upper bound yields a total PWM loss for an arbitrary operating point

\[
P_{PWM} = 4P_{MAX}v(1-v),
\]

\( v = V/V_{DC} \) - normalized PWM amplifier output voltage that equals PWM duty cycle.
6.1.2 PWM Loss Experiment for AC Permanent Motor

Permanent magnet AC motor must be back driven with such a speed that motor phase back EMF amplitude equals $0.637V_{dc}$ for a two-phase and three-phase delta connected motor. For a three-phase Y-connected motor, phase back EMF amplitude should be $0.368V_{dc}$ (phase-to-phase back EMF amplitude of $0.637V_{dc}$). Closed-loop controlled inverter with a zero current command will produce a maximum PWM loss (Figure 5). The power into the motor $P_{\text{MAX}}$ is a total PWM loss. By using PWM eddy current approximation (7) we get an upper bound of total PWM loss for an arbitrary operating condition

$$P_{PWM} = P_{\text{MAX}}\left(3.14v_A - 2.47v_A^2\right).$$

(9)

6.2 PWM Loss Experiment for AC Induction Machine

We suggest running a known PWM loss characterization / separation experiment [3, 4] for a maximum PWM loss point. Induction machine is first subject to sinusoidal voltage supply. Ideal no-load test and standard motoring no-load test are performed. After mechanical and copper losses are calculated, iron losses are identified by subtracting mechanical and copper losses from the measured input power. Input power and phase current are measured using electronic watt-meters and precision ammeters [3]. The induction machine is then tested again under no-load conditions with the same speed this time fed by PWM inverter with the same fundamental frequency. PWM loss is calculated from measured input power increase.

If induction motor PWM loss is characterized for a maximal PWM loss point, then total motor PWM loss for an arbitrary operating condition may be found using (9).

6.3 Improved PWM Loss Characterization Experiment

Induction motor PWM loss experiment [3, 4] is not that simple and accurate as it requires an experimental set up with a prime mover and sinusoidal mains, running different experiments and further PWM loss separation from mechanical and main electromagnetic process losses. We are developing a different PWM loss experiment that does not require a prime mover and sinusoidal mains. It will allow motor designers and manufacturers to make a simple effective comparison between different lamination grades / thicknesses and add accurate PWM loss graphs to motor datasheets. Motor users and drive designers will be able to easily separate motor PWM loss on their own, compare different motors / drives, switching patterns and more.
7 PWM Loss Reduction

Finally, let’s examine in brief some PWM loss reduction opportunities. One general recommendation is not to try to reduce machine PWM loss by switching frequency increase, this simply will not work! Thinner laminations reduce PWM core loss just as main flux induced rotational one.

Figure 6 illustrates a potential of two motor PWM loss reduction techniques. DC link voltage regulation while keeping maximal duty cycle without overmodulation was suggested by Prof. F. Profumo for low dynamic applications like pumps. Another opportunity is a multi-level PWM. Three-level PWM allows to reduce PWM loss more than 4 times on average compared with conventional two-level inverter.

![Normalized PWM Loss Comparison](image)

**Figure 6:** Some PWM Losses Reduction Opportunities

8 Conclusions

This paper presents a new electrical machine PWM loss time domain engineering approach. It comprises normalized PWM loss evaluation and PWM loss characterization experiment for a maximal loss (maximal current ripple) point. We assume that PWM core eddy current loss is a dominating loss mechanism that is in agreement with published experimental data, in particular, with the fact that motor PWM loss practically does not show any major switching frequency dependence.

PWM loss upper bound for an arbitrary operating point is obtained by scaling measured total maximal PWM loss using PWM eddy current envelope simple formula.

For a given power converter topology and switching pattern, PWM loss is a function of converter output voltage. Closed-form PWM loss expressions are obtained for a DC brushed motor supplied by H-bridge converter, two- and three-phase AC brushless permanent magnet and induction machines fed respectively by two H-bridges and three-phase conventional inverter. We claim two- and three-phase AC machine equiva-
ence as well as AC permanent magnet and induction machine equivalence from normalized PWM loss perspective.

We also compared such PWM loss reduction techniques as DC link regulation for low dynamic applications and three-level PWM converter. For three-level PWM, PWM loss is reduced as much as 4 times on average compared with conventional two-level inverter.

Suggested PWM loss approach is also applicable to other types of electrical machines (switched reluctance, DC brushless, doubly-fed induction machine) where closed form PWM loss solution may not be available and to different converter topologies and switching patterns. Our basic ideas are relevant to PWM loss estimation by means of a coupled field and circuit numerical analysis. Another research direction is developing simple and effective PWM loss characterization experiment that requires neither additional motor to back drive the motor under consideration nor sinusoidal mains.

9 References


Design Strategies and Different Materials for High Efficiency Induction Motors. A Comparison

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Abstract

The paper presents the results of a research project concerning the efficiency improvement in industrial three-phase induction motors, making use of three different design strategies: substitution of copper cage for aluminium cage with standard and „premium” electrical steel; design optimisation of copper cage motor by changing the stator winding and the stack length only; design optimisation of copper cage motor by changing the stator winding, the stack length and the stator and rotor slot shapes.

The aim of the project was the analysis and the construction of several prototypes of induction motors by using the above mentioned innovative technological solutions, in order: to compare the design strategies; to verify the actual efficiency improvements, the arrangement of the motors with respect to the European Classification Scheme (EC/CEMEP), the contribution of each material and innovative technology to the efficiency improvements.

The paper presents the results related to above mentioned design strategies, and concerns a typical 3 kW, 4 pole, 50 Hz, 400 V, TEFC induction motor.

The experimental results presented in the paper refer to the Standard CSA C390-98.

1 Introduction

Electric Drive Systems have a significant impact on the consumption of electricity and induction motors are one of the components involved, which can contribute to energy savings. While sensitive and technically ready, the motor industry is under increasing price competition from low cost low efficiency motors. New ranges of high efficiency motors require accurate motor design, the adoption of new materials (e.g. premium steel) and innovative technologies (e.g. copper rotor cage die-casting). The challenge is to develop high efficiency motors without substantial additional cost. That could be achieved by choosing among several design strategies each of one presents different cost for the manufacturer.

In the paper the following design strategies have been investigated:

1. Substituting copper cage for aluminium cage and standard electrical steel, without changing any motor dimension.

   It is well known that incorporation of copper for the rotor bars and end rings in place of aluminium would result in attractive improvements in motor energy efficiency (Chiricozzi et al. 2004), (Brush et al. 2003). Copper die-cast rotor construction does not differ significantly from the aluminium one and, in essence, the
manufacturing details are identical. The additional manufacturing challenges are increased temperatures and pressures required to die-cast copper: the main technical barrier was the inadequate die life of the mould. Recently suitable high temperature mould materials have been successfully identified demonstrating that operating the dies and shot sleeve at elevated temperatures could substantially extend tooling life (CDA and ICA 2004), (Brush et al. 2004). Also, the French company, FAVI SA (Fonderie et Atelier du Vlmeu), has applied its considerable experience and know-how in die casting copper alloys to the production of the copper rotors for a number of European motor manufacturers. FAVI has co-operated with the authors manufacturing a line of high-temperature moulds and several copper rotor cages (Parasiliti et al. 2004).

(2) Substituting copper cage for aluminium cage and high performance electrical steel, without changing any motor dimension.

The magnetic material plays a significant role in the improvement of the motor performance (Parasiliti et al. 2001). With respect to this goal, its main features are the magnetic permeability and the specific losses. Moreover, the choice of a „suitable“ electrical steel depends on several aspects such as cost, workability, annealing (when needed), „business tradition” and storehouse demands. ThyssenKrupp ES Acciai Speciali Terni, Italy, European leader in the production of electrical steels for electromechanical applications, has co-operated with the authors providing several electrical steels that have been used in the new prototypes.

(3) Design optimisation of copper cage motor by changing the stator winding and the stack length only.

LAFERT S.p.A., one of the most important Italian manufacturer of induction motors, has provided the stator and rotor cores and stator windings and has assembled the prototypes with copper rotor cages;

(4) design optimisation of copper cage motor by changing the stator winding, the stack length and the stator and rotor cross sectional geometry

The aim of the project was the comparison between the above mentioned design strategies with respect to:

- the efficiency improvements;
- the arrangement of the motors with respect to the European Classification Scheme (EC-CEMEP);
- the contribution of each material and innovative technology to the efficiency improvements.

The paper presents the results obtained using the considered design strategies when „premium steel“ and copper rotor cage are used instead of standard steel and aluminium cage, with standard and higher stack length. The considered motor is a typical 3 kW, 4 pole, 50 Hz, 400 V, TEFC, industrial low voltage three-phase induction motor.
2 Research Project Development

To evaluate the efficiency improvements, a commercial motor with aluminium rotor cage and standard electrical steel has been chosen as „reference motor“: it belongs to the low efficiency class Eff3 but close to the boundary with Eff2: taking into account the tolerance on efficiency measurements, the considered 3 kW motor could be classified in the Eff2 class.

The standard electrical steel used in the reference motor construction is labelled 8050. The chosen alternative electrical steel is labelled 5350H. It represents a good compromise between specific loss and permeability. In fact, frequently better magnetic materials from the losses point of view have worse permeability. As a consequence, the increase of magnetizing current and corresponding Joule losses reduce the benefit of lower iron losses. Actually, the electrical steel 5350H can be define „premium steel“ because combines low specific losses (3.5 W/kg at 1.5 T with respect to 5.5 of the 8050, Figure 1) with high permeability (better than 8050 under 1.2 T, a little bit worse over).

![Figure 1: Specific losses and B-H curves of 8050 and 5350H steels](image)

2.1 Motor Prototypes

The motor prototypes have been realized according to the following combinations.

1. aluminium cage and standard steel 8050 (commercial „reference motor“); the corresponding prototype is labelled „Al 8050“;
2. copper cage and standard steel 8050; the prototype is labelled „Cu 8050“;
3. copper cage and premium steel 5350H; the prototype is labelled „Cu 5350H“;
4. copper cage, standard steel 8050, new stator winding and Higher Stack Length (HSL); the new stack length is consistent with the standard housing; the prototype is labelled „HSL Cu 8050“;
(5) copper cage, premium steel 5350H, new stator winding and Higher Stack Length (HSL); the new stack length is the same of case 4); the prototype is labelled „HSL Cu 5350H“;

(6) copper cage, premium steel 5350H, higher stack length, new stator winding and new stator and rotor slot shapes (Optimised Design OD); the new stack length is the same of case 4); the prototype is labelled „OD Cu 5350H“;

The motor prototypes could be divided in two groups:

• the first (combinations 1÷3) includes the standard motor and the alternative ones with copper cage and premium steel with the same stator winding and stack length; they represent the cheapest way to increase the efficiency using high quality materials and innovative technology;

• the second group includes the prototypes with higher stack length, new stator winding, copper rotor cage, premium steel (combinations 4 and 5) and new stator and rotor cross sectional geometry (case 6); the inner and outer stator diameters are the same of the standard motor ones. For cases 4) and 5) the cost of tooling is effectively the same of the standard design since the need for costly new lamination punch tools or stator housing tools are avoided (except the additional cost for copper die-casting).

All new motors have been designed by a suitable design procedure that combine a performance analysis model with an optimisation algorithm.

2.2 Design Procedure

The physical description of the motor is reduced to equivalent parameters such as resistances and inductances: the adopted analytical model takes into account the influence of saturation on stator and rotor reactances and the influence of skin effect on rotor parameters. The effects of temperature on motor resistances are computed on the basis of a detailed thermal network. The validity of the model has been verified by means of experimental tests on several three-phase induction motors (Chiricozzi et al. 1997).

The design optimisation integrates the analytical motor model into an automated process. The optimisation problem is to minimise (or maximise) a function $F=F(X)$, with $X=(x_1, x_2, \ldots, x_n)$; the function $F$ is called „objective function“ (OF) and the vector $X$ represents the set of variables. Each variable might be constrained explicitly by upper/lower bounds ($x_l < x_i < x_u$ $i=1,2,3,\ldots,n$). The introduction of $p$ constraints $g_i(X)$ that concern typical motor performance makes the optimisation a constrained problem. The distinguishing features of such an optimisation problem are that:

(i) an explicit mathematical representation of the objective function and of constraint functions is not available;

(ii) the constraints $g_i(X) \leq 0$, $i=1,\ldots,p$, are not very restrictive, namely it is relatively easy to find a feasible point and to remain in the feasible region;
(iii) different local minimum points lie beside global minimum points.

The approaches proposed in literature to tackle induction motor design optimisation, use one or both the following strategies:

- the constraints $g_i(X) \leq 0$, $i=1,...,p$, are eliminated by adding to the objective function an interior penalty term which goes to infinity at the boundary of the set;
- the (possibly modified) objective function is minimized over the box $x_{li} \leq x_i \leq x_{ui}$ by adopting a derivative-free unconstrained local optimisation method; such an algorithm is able to find a stationary point of the objective function, without using first order derivatives (e.g. simplex method or the Hooke-Jeeves algorithm).

The optimisation algorithm proposed by the authors (Daidone et al. 1998) does not use any penalty function; instead, because of feature (ii) of the original problem, it is able to produce directly feasible points. Another interesting feature is that it is a modification of a method which was defined to locate the global minimum of a function and therefore it does not get trapped in local minima.

Table 1: Design variables with upper and lower bounds

<table>
<thead>
<tr>
<th>Variables</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>(*) Stack length (mm)</td>
<td>130</td>
<td>160</td>
</tr>
<tr>
<td>(*) Stator wire size (mm²)</td>
<td>0.90</td>
<td>1.30</td>
</tr>
<tr>
<td>(*) Air-gap average flux density (T)</td>
<td>0.45</td>
<td>0.60</td>
</tr>
<tr>
<td>Stator tooth width (mm)</td>
<td>3.7</td>
<td>4.3</td>
</tr>
<tr>
<td>Stator tooth height (mm)</td>
<td>15.0</td>
<td>19.0</td>
</tr>
<tr>
<td>Rotor tooth width (mm)</td>
<td>3.7</td>
<td>4.8</td>
</tr>
<tr>
<td>Rotor tooth height (mm)</td>
<td>15.0</td>
<td>18.0</td>
</tr>
<tr>
<td>(*) cases 4) and 5)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2: Design Constraints with upper/lower bounds

<table>
<thead>
<tr>
<th>Constraints</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Power factor</td>
<td>≥ 0.75</td>
<td></td>
</tr>
<tr>
<td>Temperature of stat. wind. (°C)</td>
<td>≤ 90</td>
<td></td>
</tr>
<tr>
<td>Temperature of rotor cage (°C)</td>
<td>≤ 100</td>
<td></td>
</tr>
<tr>
<td>Breakdown torque (Nm)</td>
<td>≥ 60</td>
<td></td>
</tr>
<tr>
<td>Locked rotor torque (Nm)</td>
<td>≥ 48</td>
<td></td>
</tr>
<tr>
<td>Locked rotor current (A)</td>
<td>≤ 50</td>
<td></td>
</tr>
<tr>
<td>Flux density in the stat. tooth (T)</td>
<td>≤ 1.8</td>
<td></td>
</tr>
<tr>
<td>Flux density in the rot. tooth (T)</td>
<td>≤ 1.8</td>
<td></td>
</tr>
<tr>
<td>Rated slip (%)</td>
<td>≤ 2.5</td>
<td></td>
</tr>
<tr>
<td>Stator slot fullness (%)</td>
<td>≤ 0.46</td>
<td></td>
</tr>
</tbody>
</table>

In the project the optimisation has been formulated as constrained maximisation of the objective function „rated efficiency“. The list of design variables and design constraints with their bounds are shown in Table 1 and Table 2 respectively.
Table 3 presents the main dimensions and weights of the prototypes (reference motors and new prototypes) while Figure 2 shows views of the copper rotors.

Table 3: Prototypes main dimensions and weights

<table>
<thead>
<tr>
<th>3 kW</th>
<th>Al 8050</th>
<th>Cu 8050</th>
<th>Cu 5350H</th>
<th>HSL Cu 8050</th>
<th>Cu 5350H</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stack length (mm)</td>
<td>130</td>
<td>130</td>
<td>155 (+19%)</td>
<td>155 (+19%)</td>
<td></td>
</tr>
<tr>
<td>Out. stator diam. (mm)</td>
<td>152</td>
<td>152</td>
<td>152</td>
<td>152</td>
<td></td>
</tr>
<tr>
<td>In. stator diam. (mm)</td>
<td>90</td>
<td>90</td>
<td>90</td>
<td>90</td>
<td></td>
</tr>
<tr>
<td>St. winding weight (kg)</td>
<td>2.45</td>
<td>2.45</td>
<td>2.82 (+15%)</td>
<td>3.46 (+41%)</td>
<td></td>
</tr>
<tr>
<td>Rotor cage weight (kg)</td>
<td>Al 0.74</td>
<td>Cu 2.43</td>
<td>2.73 (+12%)</td>
<td>2.89 (+19%)</td>
<td></td>
</tr>
<tr>
<td>Gross iron (kg)</td>
<td>22.4</td>
<td>22.4</td>
<td>26.8 (+20%)</td>
<td>26.8 (+20%)</td>
<td></td>
</tr>
</tbody>
</table>

Figure 2: Views of copper rotors, 3 kW motor

3 Results

In order to evaluate the copper rotor and premium steel effects on each loss category and to obtain an accurate efficiency measurement, a loss segregation method is required. IEEE 112-B and CSA C390-98 methods are true input vs output power efficiency tests that segregate losses into five categories: Iron Losses, Stator Resistance, Rotor Resistance, Friction and Windage (F&W) and Stray Load Losses (SLL). The first four are measured directly and the remainder is the „stray load“ category. The experimental results presented in the paper refer to the Standard CSA C390-98.

Table 4 shows the comparison between standard length new prototypes (Cu 8050 and Cu 5350H) and commercial motor Al 8050: the efficiency and loss segregation test results are presented.

Comparison between motors Al 8050 and Cu 8050 allows to evaluate the improvements achievable with copper rotor only. The comparative tests have been carried out
by adopting the same stator core and winding: in this way any difference in performance due to the production process has been avoided.

Motor Cu 5350H results shows the effects of the premium steel (in comparison with motor Cu 8050) and the improvements with respect to the standard motor (in comparison with motor Al 8050).

Table 4: CSA C390-98 Efficiency and Loss Segregation Test Results. 3 kW standard stack length motors

<table>
<thead>
<tr>
<th>3 kW</th>
<th>Al 8050</th>
<th>Cu 8050</th>
<th>Cu 5350H</th>
</tr>
</thead>
<tbody>
<tr>
<td>η %</td>
<td>82.0</td>
<td>84.1 (+2.1)</td>
<td>84.5 (+2.5)</td>
</tr>
<tr>
<td>Σ losses (W)</td>
<td>655</td>
<td>563 (-14%)</td>
<td>545 (-17%)</td>
</tr>
<tr>
<td>Stator wind.</td>
<td>351</td>
<td>327</td>
<td>337</td>
</tr>
<tr>
<td>Rotor cage</td>
<td>153</td>
<td>83 (-46%)</td>
<td>83 (-46%)</td>
</tr>
<tr>
<td>Iron</td>
<td>117</td>
<td>124</td>
<td>94 (-20%)</td>
</tr>
<tr>
<td>SLL</td>
<td>13</td>
<td>13</td>
<td>8</td>
</tr>
<tr>
<td>F&amp;W</td>
<td>21</td>
<td>16</td>
<td>23</td>
</tr>
</tbody>
</table>

The substitution of copper as rotor material has allowed to move the 3 kW motor in the Eff2 class (efficiency > 82.6), while the use of the 5350 H electrical steel does not give rise any further efficiency class movement. As expected, the most significant loss reduction is in the rotor cage while iron losses reduction is 20 % with premium steel.

Further improvement on motor performance has been achieved with copper rotor and premium steel adoptions combined with higher stack length, new stator winding (motors HSL Cu 8050 and HSL Cu 5350H) and new stator and rotor slot shapes (motors OD Cu 5350H). Table 5 shows test results of the 3 kW higher stack length prototypes.

Table 5: CSA C390-98 Efficiency and Loss Segregation Test Results. 3 kW Higher Stack Length motors

<table>
<thead>
<tr>
<th>3 kW</th>
<th>HSL Cu 8050</th>
<th>HSL Cu 5350H</th>
<th>OD Cu 5350H</th>
</tr>
</thead>
<tbody>
<tr>
<td>η %</td>
<td>86.0</td>
<td>86.5</td>
<td>87.7</td>
</tr>
<tr>
<td>Σ losses (W)</td>
<td>486</td>
<td>465</td>
<td>418</td>
</tr>
<tr>
<td>Stator wind.</td>
<td>265</td>
<td>265</td>
<td>186</td>
</tr>
<tr>
<td>Rotor cage</td>
<td>73</td>
<td>77</td>
<td>67</td>
</tr>
<tr>
<td>Iron</td>
<td>113</td>
<td>99</td>
<td>134</td>
</tr>
<tr>
<td>SLL</td>
<td>15</td>
<td>9</td>
<td>8</td>
</tr>
<tr>
<td>F&amp;W</td>
<td>20</td>
<td>15</td>
<td>23</td>
</tr>
</tbody>
</table>

With standard steel 8050 the measured efficiency is 2 points higher with respect to the corresponding copper rotor motor with standard stack length and 4 points higher with respect to the commercial aluminium rotor motor (Table 4). With premium steel 5350H the measured efficiency is 2 points higher with respect to the corresponding copper rotor motor with standard stack length and 4.5 points higher with respect to the com-
Commercial aluminium rotor motor. The most significant losses reduction is in the stator winding. The HSL motors remain in the Eff2 class, but could be labelled Eff1 motors if the tolerance is taken into account.

The best results have been achieved when the adoption of new materials and innovative technologies have been associated with a more complete, accurate optimised motor design (OD Cu 5350H motor) that allows to exploit the advantages of copper cage and premium steel: the motor is fully in Eff1 class (efficiency > 87.4). Stator winding losses are considerably reduced, only partially compensated by the iron losses increasing due to the higher flux densities; moreover, further rotor cage losses reduction has been obtained.

A complete comparison between the motor series is shown in the next figures.

Figure 3 shows the dependence of efficiency on output power. It is easy to individuate four groups of motors: standard motor with aluminium; motors where aluminium are simply substituted by copper; motors with higher stack length; motor completely redesigned. The effects of materials (premium steel and copper) and design strategies are evident. Curves corresponding to copper cages are almost flat, maintaining good efficiency in an extended range (0.6÷1.2 p.u.) of output power with respect to aluminium motor (0.6÷1.0 p.u). That result is important due to frequent partial load operations and shows good overload capabilities of copper rotor motors.

Figure 4 presents the voltage-no load current curves. It points out the effect of the design optimisation exploiting the quality of the premium steel.

Figs. 5 shows the comparison between other important motor performance.

Stator winding temperature rise reduction confirms the total losses trend and it is between 30 °C and 40 °C for the new design motors. That is a very important feature because temperature rise is significant in the life expectancy of the motor and lower temperatures mean that smaller cooling fans can be used: this has a significant effect in reducing the friction and windage losses.

Power factor is almost constant for all motors with the exception of the OD Cu 5350H optimised design one.

Copper substitution for aluminium keeps nearly constant the breakdown torque. Higher stack length and new stator winding permit to increase it by 15 %.

Focusing on starting conditions, the substitution of copper for aluminium leads to decreased starting torque (~13 ÷ -20 %, but still above two times the rated one) and slight higher starting current (+ 14%). Higher stack length and new stator winding assure the same standard motor locked rotor torque with about 40 ÷ 45 % higher currents.
4 Conclusions

The paper presents test results concerning several prototypes of a 3 kW induction motor with die-cast copper rotor cage and premium electrical steel.

Three design strategies have been investigated:

(1) substituting copper cage for aluminium cage with standard and high quality electrical steel, without changing any motor dimension;

(2) design optimisation of copper cage motor by changing the stator winding and the stack length only;

(3) design optimisation of copper cage motor by changing the stator winding, the stack length and the stator and rotor cross sectional geometry.

The substitution of copper for aluminium has allowed to move the motor in the Eff2 class.

Motors with higher stack length and optimised new stator winding (HSL series) remain in the Eff2 class, but could be labelled Eff1 motors if the tolerance is taken into account.

Motor is fully in Eff1 class if new stator and rotor slot shapes are adopted, when an accurate optimisation allows to exploit the advantages of copper cage and premium steel.

All copper rotor motors assure flat efficiency-output power curves. Motors with new design guarantee lower stator winding temperature, higher breakdown torque and constant locked rotor torque. New lamination adds higher power factor.

5 References

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Figure 3: Efficiency - output power curves

![Efficiency - output power curves](image)

Figure 4: Voltage - no load current curves

![Voltage - no load current curves](image)
Figure 5: Comparison between the motor series
Influence of the Rotor Slit Depth on the Performance of the Solid-Rotor Induction Motor

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D.Sc. Janne Nerg, Prof. Juha Pyrhönen, Lappeenranta University of Technology, Dep. of Electrical Engineering, Finland

Abstract

The polyphase induction motor with solid iron rotor offers undoubted advantages in terms of construction simplicity and strength over conventional induction motors when the elevated rotation speed is needed. In this paper a three-phase induction motor with slitted solid-rotor is analyzed using two-dimensional finite-element method. Different rotor designs are studied in order to find out the influence of the rotor slit depth on the motor performance characteristics. It was found that the rotor slits should reach very deep inside the rotor. The depth of the rotor slitting is restricted by the saturation of the rotor material between the slits. Also the mechanical strength of the rotor material limits the depth of the rotor slitting. It is shown that in order to reduce the mechanical stress and the saturation of the rotor material between the slits the slitting should be made in such a way that every second slit is deeper than the other.

1 Introduction

The advancement of technology is very closely associated with the increase of the operational speed in almost all the branches in industry. For achieving high speed, high frequency electrical machines are always the preferable choice. The idea of using high-speed machines, which are rotating at higher speeds than it would be possible to directly reach by means of the network frequency, is to replace a mechanical gearbox by an electrical one and attach the load machinery directly on the motor shaft. The losses due to the mechanical gearbox are thus avoided and a full speed control for the drive is achieved. The other advantages of using high-speed electrical machines are the reduction in size per unit output power and improvement in drive train efficiency.

The development of cost effective power converters for high power opens the market for high-speed drives. The ongoing progress in the field of power electronics helps to realize power converters for higher frequencies at lower cost than in the past making the use of high-speed electrical drives an attractive alternative to the traditional solutions and thus achieve significant improvement in the efficiency. The high-speed electrical machines find their applications in pumps, compressors and for various purposes in scientific and advanced engineering research (Sharma et al. 1996).

The most common type of the high-speed machine used in industrial applications is a poly-phase solid-rotor induction motor. Solid-rotor induction motors are built with a rotor core made of a solid single piece of ferromagnetic material. The simplest solid rotor is, in fact, a smooth steel cylinder. This kind of a rotor is easy to manufacture and it has the best mechanical and fluid dynamical properties. The electromagnetic properties of
such a rotor are, however, quite poor, as, e.g. the slip of the rotor tends to be large and the power factor low. The reason why solid rotors are used at high-speed operation is that the traditional rotor structure, i.e. laminated rotor core with a squirrel cage, is not able to withstand the high rotational and thermal stresses caused by the high circumferential velocity of the rotor.

The research in the field of solid-rotor induction motors was quite intensive from 1960’s to mid 1980’s. Most of the published articles were concentrated on the analytical modelling of the solid-rotor induction motor, the most important results of which can be found e.g. in (Bergman 1982), (Chalmers et al. 1982) and (Yee et al. 1972). At the end of 1980’s the interest in the utilization of solid-rotor induction motors in high-speed technology in Finland was started. The effects of the solid-rotor material on machine characteristics were studied in (Pyrhönen 1991). Thermal modelling of solid-rotor induction motor was reported in (Saari 1998) and maybe the two most comprehensive studies considering the electromagnetic calculation and design of high-speed solid-rotor induction machine are published in (Huppunen 2004) and (Lähteenmäki 2002).

It is well known fact that the torque of the solid-rotor induction motor can be improved using copper end-rings. According to (Huppunen 2004), a smooth solid-rotor equipped with copper end-rings produces twice as much torque at a certain slip as the same rotor without end-rings. The second performance improvement in a solid rotor can be achieved by slitting the cross section of the rotor in such a way that a better flux penetration into the rotor will be enabled. Slitting the rotor decreases the low frequency impedance of the rotor thus producing more torque, and increases the high-frequency surface impedance of the rotor thus decreasing the rotor eddy-current loss. The drawback of the axial slitting is that at very high speeds the friction between the rotating rotor and air increases. Slitting also lowers the mechanical strength of the rotor. Although the benefits of rotor slitting are known, relatively little has been published on the effect of the rotor slitting on the performance characteristics of the solid-rotor induction motor. According to (Jinning et al. 1987) the optimal number of slits is between 5 and 15 per pole pair. The optimal depth of a slit equals approximately the magnetic flux penetration depth and the ratio between the slit width and the slit pitch is between 0.05 and 0.15. A slitted solid-rotor induction motor was analyzed in (Zaim 1999) by means of a FEM program, but only a few rotor slit parameters were used.

The aim of this paper is to numerically study the effect of the axial rotor slit depth on the torque production and on the power factor of the high-speed solid-rotor induction motor. Several different rotor designs are studied and their effect on the motor torque and power-factor are compared with the results obtained from the smooth rotor. Also the slitting strategy where every second slit is deeper than the other is studied.

2 The test motor and method of analysis

The test motor was a three-phase, 200 kW, 170 Hz, two-pole, solid-rotor, high-speed induction motor. Different rotor designs were studied in order to find out the influence of the rotor slit depth on the motor performance characteristics. Due to the constraints set
by the rotor manufacturing process the rotor slit shape was selected to be rectangular. The width of the slit was selected to be a practical constant of 2.5 mm. The rotor core material was Fe-52C and the outer diameter of the rotor was 195 mm in all calculations. The number of stator slots was 48 and the same stator was used in all the calculations. The analyzed rotor geometries were a smooth solid-rotor, a slitted solid-rotor with an equal slit depth and a slitted solid-rotor where every second slit was deeper than other. The number of rotor slits was 34. The cross-sections of studied rotor constructions are presented in Figure 1.

![Figure 1: Cross-sections of the solid-rotor constructions studied: a) Smooth solid-rotor, b) Slitted solid-rotor with an equal slit depth and c) Slitted solid-rotor, where every second slit is deeper than the other.](image)

A two-dimensional finite element analysis was chosen in finding the correlation between the motor performance characteristics and the rotor parameters by varying the slitting strategy and slit depths. FEM based analysis was chosen because, in order to find an optimal slitted solid-rotor design, analytical solving methods cannot be used directly, since the model with substitute parameters are differing in a considerable way from the real electromagnetic phenomena of the motor.

Torque versus slip and power factor versus slip characteristics were calculated using a two-dimensional, non-linear, time-stepping finite element analysis. The time-stepping analysis was selected in order to include the effects of the geometry variation i.e. the movement of the rotor with respect to the stator, into account. The electromagnetic field of the motor in the Cartesian plane can be described in terms of magnetic vector potential \( A \) as

\[
\nabla \nu \nabla A + \sigma \left( \frac{\partial A}{\partial t} \right) = J, \quad (1)
\]

where \( \nu \) is magnetic reluctivity, \( \sigma \) is electric conductivity, \( t \) is time and \( J \) is the current density. In order to take the end winding effects of the stator into account equation (1) is coupled with a circuit equation.
Influence of the Rotor Slit Depth on the Performance of the Solid-Rotor Induction Motor

where \( u \) and \( i \) are the voltage and the current of the winding, \( R \) is the resistance of the winding, \( \psi \) is the flux linkage associated with the two-dimensionally modeled magnetic field and \( L_{ew} \) is the end-winding inductance, representing the part of flux linkage, which is not included in \( \psi \). The comparison of the measured and calculated torque versus slip characteristics of a slitted solid-rotor with a slit depth of 40 mm is presented in Figure 2.

The rotor end effects are taken into account by increasing the rotor material resistivity in the calculations by the end factors (Huppunen 2004). The difference between measured and calculated torque in Figure 2 is due to the saturation of the end region of the solid-rotor. The end region of the solid rotor drifts in deeper saturation while the slip increases and thus enlarging the calculation error. When the slip is 1.5 per cent, the error between the measured and the calculated torque is 6 per cent. When the torque is considered the computation method used is accurate enough at low slip values. In order to take the end-field effects of the rotor into account, a full three-dimensional finite element analysis is required. The modeling of the whole solid-rotor induction motor with 3-D FEM is, however, too large a problem to modern computers. This is because the problem is a three-dimensional non-linear eddy-current problem and the vector potential is to be solved within the whole rotor volume. This increases the number of unknown variables extremely large. Furthermore, the rotor volume must be modelled using edge elements in order to ensure the current flow to one element to another to be

\[
u = R i + L_{ew} \frac{di}{dt} + \frac{d\psi}{dt},
\]
The use of the edge elements makes the convergence more difficult than it is in the case of nodal elements.

3 Results

Let us first consider a smooth solid-rotor. As the Lorenz force states, the electromagnetic torque is due to the interaction between the eddy currents induced in the solid cylindrical rotor and the air-gap rotating magnetic field. Unfortunately, as a result of the skin and proximity effects, eddy currents at the surface of the ferromagnetic, electrically conducting rotor core material tend to push the induced magnetic field outwards in the rotor and the magnetic flux is pressed near the surface of the solid-rotor. Thus, the depth of penetration into the rotor is extremely low and the magnetic flux and the torque producing eddy-currents are concentrated at the surface layer of the rotor thus saturating the surface of the rotor. Because of the magnetic saturation of the rotor surface the inner part of the rotor core becomes useless. The flux lines and the flux density distribution of the cylindrical smooth solid-rotor at 1.5 per cent slip are shown in Figure 3.

When the solid-rotor is axially slitted, the axial rotor tooth forms a path for eddy currents to flow from one rotor end to the other. The eddy-current passing through the rotor tooth creates a magnetic flux circulating around the current path. Compared with the smooth rotor, a better magnetic flux penetration into the rotor is enabled. By making grooves parallel to the axis of the solid rotor the reluctance of the tangential flux path increases and saturation together with eddy current loss decreases. The slits coerce the flux on its way to the other magnetic pole to penetrate as deep as the slits are and the considerable performance improvement of the motor can be achieved. The flux lines and the flux density distribution of the slitted solid-rotor at a slip of 1.5 per cent are shown in Figure 4.

Figure 3: Flux lines and flux density distribution of a smooth solid-rotor induction motor at a slip of 1.5 per cent
Influence of the Rotor Slit Depth on the Performance of the Solid-Rotor Induction Motor

Figure 4: Flux lines and flux density distribution of a slitted solid-rotor induction motor at a slip of 1.5 per cent. The rotor torque producing eddy-currents now penetrate much deeper than in the smooth rotor case.

By comparing figs 3 and 4, the current penetration in the axially slitted rotor is considerably better than it is in the case of a smooth rotor and thus better torque production is achieved.

Figure 5: Influence of the rotor slit depth on the electromagnetic torque as a function of slip

The effect of the rotor slit depth on the electromagnetic torque of the motor as a function of slip is shown in Figure 5. In the calculations the rotor slit depth was varied from 5 mm to 70 mm and the torque obtained from the smooth rotor was kept as a reference.
value. As it is seen in Figure 5, the effect of the depth of the rotor slits on the generated torque is very significant. When all the rotor slits are kept in the same depth, the optimal depth is 60 mm, which is about 60 per cent of the rotor radius. If the depth of the rotor slits is left to 30 mm, the generated electromagnetic torque is 20 per cent lower than in the previous case. The depth of the rotor slitting is restricted by the saturation of the rotor core material between the slits. Furthermore, the mechanical strength of the rotor material limits the depth of the rotor slitting.

![Figure 6: Influence of the rotor slit depth on the motor power factor](image)

The effect of the rotor slit depth on the power factor of the motor as a function of slip is presented in Figure 6.

It is seen from Figure 6 that the power factor obtained from the smooth rotor is very low. By means of slitting the solid rotor, the power factor is improved closer to acceptable level. The power factor of the motor achieves its maximum value when the depth of the rotor slits is 60 mm. The improvement in power factor via slitting the rotor is also very significant because present day users of electrical motor drives are demanding and looking for a higher power factor. The higher the power factor, the more effectively the electrical power is being used.

As it was earlier mentioned, the depth of the rotor slitting is restricted by the saturation of the rotor material between the slits. When the rotor slitting reaches deep inside rotor core, the rotor core material between the slits is highly saturated and the flux flow in the rotor teeth is restricted. Also the mechanical strength of the rotor material set limits for the rotor slitting, i.e. in the case of the studied rotor the rotor constructions with over 50 mm deep slitting could be mechanically too fragile. A good rule of thumb, as for the
electric properties of the machine, is that the slit depth should be about half of the rotor radius. In order to achieve deeper slitting and to reduce both the mechanical stress and the saturation of the rotor material between the slits the slitting can be made in such a way that every second slit is deeper than the other. The calculated electromagnetic torque and the power factor with using equal slit depth and in the case of using the slitting strategy where every second slit is deeper than another at a slip of 1.5 per cent are presented in Figure 7.

![Figure 7: Electromagnetic torque and the power factor of the motor with different rotor slitting strategies at 1.5 per cent slip](image)

It may be seen in Figure 7 that the electromagnetic torque as well as the power factor of the motor reach their maximum values when equal slit depth of 60 mm is used. The slitting combination where every other slit is 40 mm deep and the other 60 mm gives quite similar results when the electromagnetic torque and power factor are considered. It can be concluded that for electromagnetic phenomena are considered the rotor slitting should be made using equal slit depth. However, for the mechanical reasons the slitting technique where every other slit is deeper than the other is a more preferable choice.

### 4 Conclusions

The appropriate rotor design is one of the most important aspects in order to get successful performance of a high-speed solid-rotor induction motor. The use of a smooth solid rotor is not profitable, because by milling axial slits into the rotor considerably bet-
ter electromagnetic torque and power factor can be achieved. The drawback in the axial slitting is that at very high speeds the friction between the rotating rotor and air increases and the rotor also becomes mechanically weaker.

The depth of a rotor slits has a significant effect on the motor performance. It was shown that the rotor slits should reach very deep inside the rotor, but there should also be enough space for the magnetic flux to flow to the other pole. Although the deeper slitting provides quite a good torque generation capability, the mechanical strength of the rotor construction is too weak. Practical maximum value of the rotor slit depth is approximately one half of the radius of the solid-rotor. It was also shown that in order to reduce the mechanical stress and the saturation of the rotor material between the slits the slitting should be made in such a way that every second slit is deeper than the other.

5 References


Electric Motors II
Energy Conservation through Efficiency Improvement in Squirrel Cage Induction Motors by Using Copper Die Cast Rotors

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Abstract
In today’s power production and utilization scenario, various types of problems are faced such as Depletion of fossil fuel sources, Increase in fuel cost, Deterioration of ecological balance due to carbon emission, Transmission and Distribution losses, Higher energy consumption due to poor efficiency drives and increased demand due to development taking place in many areas of the world which were hitherto undeveloped / under developed. Many of these problems can be addressed by adopting suitable technology resulting in energy saving. Energy conservation through Energy Efficiency is the need of the hour and Mehala has adopted this as motto and attempting to achieve this by developing higher efficiency motors with Copper Rotor Motor Technology. Our immediate focus is on motors of small/medium ratings from 0.18kW to 18.5kW where the technology of Die cast copper rotors seems easily feasible and the contribution to efficiency improvement is seen substantial. The presentation covers experience of M/s Mehala so far and provides details of efficiency improvements, Energy saving potential, case studies, pump application and further needs and tasks regarding the technology.

In 1883, Nikola Tesla, an American scientist invented the squirrel cage induction motor. In 1891, a crude type of this motor was exhibited at the Frankfurt Exhibition and regular production of these motors was started around 1898. The squirrel cage induction motor was introduced as a boon to the industrialization of 20th century.

The details under chapter 1, 2, 3, 4 & 5 cover a broad background of technology and concern for efficiency to understand and appreciate the relevance and contribution of the new development and improvement.

1 Problems faced in brazed copper bar rotor motors

In the initial stages, ‘copper bars’ were used as rotor conductors which were inserted into rotor slots and brazed to the copper end rings to form the squirrel cage rotor.

The copper bars driven into the slot, tend to leave air gaps around the bars, giving rise to ineffective heat transfer.

The soundness of the brazing always remained questionable and the brazing tends to crack under conditions of vibration. The brazed sections of end rings were never uniform. The process often resulted in non uniform electrical and vibration characteristics.
2 Why and how Aluminium die cast rotors came into existence

As squirrel cage motors started dominating the Industrial scene, R&D got on to eliminate or minimize the rotor problems of the brazed construction.

Then as a technology improvement and enabling mass and defect free production, the die cast Aluminium rotors got developed totally eliminating bars insertion and end rings brazing etc. This successful development was readily adopted all over and today it dominates the entire world of LT squirrel cage induction motors.

3 Awareness for Energy efficiency

The awareness about energy efficiency arose due to the following reasons:

- Increasing fuel cost and depleting fossil fuels and crude.
- Increasing energy bills
- Ever increasing demand for energy
- High capital investment in new power projects (1kWhr saved equals 2kWhr generated.)
- Ecology unbalance due to carbon emission
- Increasing subsidies for agricultural sector and preferential industries in many countries.
- A global survey which cautioned that most of the conventional sources will be available upto the year 2250 only.

It was logically concluded that the economical way to offset the above problem considerably was to reduce losses by increasing efficiency.

3.1 International recommendations on Energy Efficiency

Due to the pressure of energy shortages, energy cost and environmental considerations various Government/non-Government agencies throughout the world started looking at the ways of improving the efficiency and creating awareness amongst the industry by enacting mandatory laws/modifying standards for voluntary adoption.

Comparative picture of laws and standards as established today in USA, EU and India is given below:
Table 1: International Recommendations on Energy Efficiency

<table>
<thead>
<tr>
<th>Legislation</th>
<th>USA (EPACT)</th>
<th>EU (CEMEP AGREEMENT)</th>
<th>INDIA (ENERGY CONSERVATION ACT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of EE motor</td>
<td>3 Phase Induction</td>
<td>3 Phase Induction</td>
<td>3 Phase Induction</td>
</tr>
<tr>
<td>Ratings</td>
<td>0.75 kW – 150 kW</td>
<td>1.1 kW – 90 kW</td>
<td>0.37 kW – 160 kW</td>
</tr>
<tr>
<td>Polarity</td>
<td>2, 4 &amp; 6 Pole</td>
<td>2 &amp; 4 Pole</td>
<td>2, 4, 6 &amp; 8 Pole</td>
</tr>
<tr>
<td>Efficiency Standard</td>
<td>Minimum Specified</td>
<td>Minimum EFF category to be labelled</td>
<td>Minimum Specified as per IS : 12615</td>
</tr>
<tr>
<td>Testing Specification</td>
<td>IEEE – 112 B</td>
<td>IEC 600 34.2</td>
<td>IS 12615</td>
</tr>
<tr>
<td>Minimum Efficiency Specified (11kW, 4 Pole, TEFC)</td>
<td>91.0 % (60 Hz)</td>
<td>88.4 % (50 Hz)</td>
<td>88.4 % (50 Hz)</td>
</tr>
</tbody>
</table>

4 Why focus on Energy Efficiency of electrical motors?

- Due to simple construction and cost effectiveness, electric motors came to dominate the entire areas of application for any motion required for carrying out a work.
- Two-third (2/3) of electricity generated globally is used to run motors, which is almost 2 Trillion (2 × 10^{12}) KWhr/Year.
- Hence, more than in any other areas, improving efficiency of motors caught the attention of government bodies, Producers and consumers of electricity, designers and manufacturers of motors.
- Improvement in efficiency of motors assumes more significance in India where motors consume over 75% of the electrical energy with very wide coverage of industrial, agriculture and rural sectors.


Figure 1: Energy consumption of motors in India (year 2003)
5 What is an Energy Efficient Motor?

An ‘Energy Efficient’ motor produces the same shaft output (hp), but absorbs less input power (kW) than a standard motor.

Efficiency = \frac{\text{Output}}{\text{Input}} = \frac{\text{Input} - \text{Losses}}{\text{Input}}

= 1 - \frac{\text{Losses}^*}{\text{Input}}

* Lesser the loss, higher the efficiency.

The efficiency can be improved by reducing the various losses in motor.

Table 2: Losses encountered in induction motor

<table>
<thead>
<tr>
<th>S.No.</th>
<th>MOTOR COMPONENT LOSS</th>
<th>SHARE ON TOTAL LOSS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Stator copper loss</td>
<td>37%</td>
</tr>
<tr>
<td>2</td>
<td>Rotor copper (Conductor) loss</td>
<td>18%</td>
</tr>
<tr>
<td>3</td>
<td>Iron Loss</td>
<td>20%</td>
</tr>
<tr>
<td>4</td>
<td>Friction and Windage loss</td>
<td>9%</td>
</tr>
<tr>
<td>5</td>
<td>Stray loss</td>
<td>16%</td>
</tr>
</tbody>
</table>

Various attempts are made to reduce the above category of losses in induction motors and we at Mehala have taken up primarily to reduce rotor copper loss using CRM (Copper Rotor Motor) technology.

6 What is Die cast copper Rotor motor and what it can do?

Copper is after all the best conductor of electricity and the question arose only towards the end of last century as to ‘ Why not copper Die cast Rotors?’ The main hurdles were the high melting temperature, high heat conductivity and low die life and some more problems.

The Die cast copper rotors can provide either of the following advantages to motor manufacturers.

1. Improvement in motor efficiency in operation through loss reduction of about 15% to 20%

2. Reduction in overall manufacturing cost and weight of the motor for the given value of motor efficiency.

Apart from various impressive advantages, Die cast copper rotors also provide a very good flexibility and scope for the designers for achieving wide range of performance and efficiencies to suit different needs and specifications.
6.1 Energy conservation by Copper Rotor Motor

A world wide survey says that

- Two-third (2/3) of electricity generated globally is used to run motors, which is almost 2 Trillion ($2 \times 10^{12}$) KWhr/Year
- 8.5% of all electricity is consumed to meet the loss in Electrical motors. Of these, motors upto 20HP constitute approximately two third of losses (i.e.) 5.4% of all electricity is wasted as loss for these motors.

The Copper die cast Rotor motor which improves efficiency by 1.5% point would save

- 30 Billion ($30 \times 10^9$) KWHr/year
- At 10 Cents / KWHr, this amounts to $3$ Billion
- Equivalent to 78 Million Barrels of oil.

[For this calculation a minimum of 1.5% is taken, though better improvements are seen in copper die cast rotors tested by us. The loss reduction is in $I^2R$ loss in the rotors and possibly some reduction in stray losses in the rotor]

6.2 Copper Rotor Motor (CRM) – The Economical way of energy conservation

The task of efficiency improvement by various methods is illustrated in chart below for a sample rating of motor. Our experience is that CRM helped to achieve efficiencies to meet EFF1 standards. It also gave confidence that with optimisation of design. It may be possible to achieve efficiencies above EFF1 level also.

![Figure 2: Technology Vs Efficiency of induction motors](chart.png)
In conventional design, the cost of motor increases while attempting to reduce the losses.

Figure 3: Induction motor Efficiency Vs Technology Vs Cost

The CRM Technology increases the efficiency of motor with a nominal increase in cost. As seen in the above graph, the CRM technology is the best way in the 21st century to increase the motor efficiency above the premium level.

6.3 Case studies

Case studies were conducted in popular ratings of textile motors in India as textile industry is one of the largest industrial sectors and the segregation of losses observed is given below.

Table 3: Test readings of 7.5 kW, 4 Pole, 50Hz motor

<table>
<thead>
<tr>
<th>Types of Losses and performance parameters</th>
<th>Standard Efficiency motor (With Al. Die cast rotor)</th>
<th>Energy Efficiency motor (with Al. Die cast rotor)</th>
<th>Energy Efficiency motor (with Copper die cast rotor)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant loss (Iron loss + Friction and Windage loss)</td>
<td>561 W (40 %)</td>
<td>298 W (35.6 %)</td>
<td>298 W (40.2 %)</td>
</tr>
<tr>
<td>Stator copper loss</td>
<td>458 W (34 %)</td>
<td>302 W (36.2 %)</td>
<td>302 W (40.7 %)</td>
</tr>
<tr>
<td>Rotor copper loss</td>
<td>312 W (23 %)</td>
<td>198 W (23.7 %)</td>
<td>116 W (15.6 %)</td>
</tr>
<tr>
<td>Stray loss</td>
<td>37 W (3 %)</td>
<td>37 W (4.5 %)</td>
<td>25 W (3.4 %)</td>
</tr>
<tr>
<td>Rpm</td>
<td>1440</td>
<td>1460</td>
<td>1470</td>
</tr>
<tr>
<td>Efficiency</td>
<td>84.5 %</td>
<td>90.0 %</td>
<td>91.0 %</td>
</tr>
<tr>
<td>Cost</td>
<td>100%</td>
<td>110.2%</td>
<td>114.5%</td>
</tr>
</tbody>
</table>
Relative costs are summed up for each rating as per our present experience (which needs further verification and work).

Table 4: Test readings of 11 kW, 4 Pole, 50Hz motor

<table>
<thead>
<tr>
<th>Types of Losses and performance parameters</th>
<th>Standard Efficiency motor (With Al. Die cast rotor)</th>
<th>Energy Efficiency motor (with Al. Die cast rotor)</th>
<th>Energy Efficiency motor (with Copper die cast rotor)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant loss (Iron loss + Friction and Windage loss)</td>
<td>650 W (39.5 %)</td>
<td>500 W (45 %)</td>
<td>500 W (50.5 %)</td>
</tr>
<tr>
<td>Stator copper loss</td>
<td>580 W (35.2 %)</td>
<td>300 W (26 %)</td>
<td>300 W (20.3 %)</td>
</tr>
<tr>
<td>Rotor copper loss</td>
<td>340 W (20.7 %)</td>
<td>258 W (22.5 %)</td>
<td>160 W (16.2 %)</td>
</tr>
<tr>
<td>Stray loss</td>
<td>75 W (4.5 %)</td>
<td>75 W (6.5 %)</td>
<td>30 W (3 %)</td>
</tr>
<tr>
<td>Rpm</td>
<td>1455</td>
<td>1465</td>
<td>1475</td>
</tr>
<tr>
<td>Efficiency</td>
<td>87.0 %</td>
<td>91.0 %</td>
<td>92.0 %</td>
</tr>
<tr>
<td>Cost</td>
<td>100 %</td>
<td>110.5%</td>
<td>115.6%</td>
</tr>
</tbody>
</table>

This goes to prove that the die cast Copper Rotor motor is the only economical way of improving the efficiency above the premium level.

6.4 Sample working of Energy Savings and payback

Assumptions: 600hrs/month, 10 cents per unit, Cost of 11kW motor is $350 with 87% efficiency

Working:
Increased cost of motor with 91% efficiency is $30
Increased cost of motor with 92% efficiency is $50
X - Input power per hour for 87% efficiency motor = 11/0.87 = 12.6 units
Y – Input power per hour for 91% efficiency motor = 11/0.91 = 12.08 units
Z – Input power per hour for 92% efficiency motor = 11/0.92 = 11.9 units
Reduction in electricity cost for 91% efficiency motor per month = (X-Y)*600*0.1 = $31.2
Reduction in electricity cost for 92% efficiency motor per month = (X-Z)*600*0.1 = $42
Hence payback of incremental cost is less than 2 months for both the cases.

7 Standards on Efficiency level

Many countries have brought forward/modified standards with a view to emphasize efficiencies in electrical motors. Some of which are:
Table 5: Standards followed in various countries

<table>
<thead>
<tr>
<th>Country</th>
<th>Standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>International</td>
<td>IEC 34 – 2</td>
</tr>
<tr>
<td>Canada</td>
<td>CSA 390</td>
</tr>
<tr>
<td>United States</td>
<td>IEEE 112</td>
</tr>
<tr>
<td>Britain</td>
<td>BS – 269</td>
</tr>
<tr>
<td>Japan</td>
<td>JEC – 37</td>
</tr>
<tr>
<td>India</td>
<td>IS 12615</td>
</tr>
</tbody>
</table>

7.1 Mehala Machines India Limited meets the standards

Based on the results of the project carried out by International Copper Promotion Council (India) at Coimbatore, establishing efficiency improvements through use of die cast copper rotors, M/s Mehala decided to design and manufacture energy efficiency motors, meeting the latest standards with this new technology.

Mehala manufactures motors in two efficiency levels of EFF1 and EFF2 with copper die cast rotors. These motors with copper die cast rotors have been certified for CSA-C/US marking and attested for CE as well. Mehala also propose to get the certification of energy efficiency. In fact it has been acknowledged that Mehala is the first Asian Manufacturer certified by CE/CSA for copper rotor motor for EFF1 & EFF2 level of efficiencies. Hundreds of copper die cast energy efficient motors manufactured by Mehala are working successfully throughout India.

The results and field tests are encouraging and M/s Mehala is planning investments to establish our own facilities for manufacturing copper die cast rotors.

8 Problems faced by Mehala in CRM project

The cost of CRM is higher by about 20% as compared to the motors of existing efficiency levels when replacing aluminium by copper die casting without any other change. In order to offset the above problems the following solutions are identified by Mehala.

1. Development of dedicated motor design and configurations of laminations optimized for CRM’s
2. Identifying and sourcing of appropriate electrical steel for the core packs.
3. Although Mehala has launched several hundreds of motors with copper die cast rotors the need for a more perfected technology of melting and die casting is felt by experience. In this regard Mehala aims for a perfected die casting technology capable of mass producing rotors at an affordable cost.
4. M/s mehala hence presently sourced the copper die cast rotors from the party in India, who developed these rotors with the help & suggestions from ICA. We are trying to acquire the know how to establish our own facilities and are confident of effecting further improvements.
9 Test results of Mehala motors

The following tests are conducted in Mehala Machines India Limited by replacing the copper die cast rotors in the place of aluminium die cast rotors without changing the other parameters. The test method followed is Losses separation method of CSA 390 and the test conditions are 3 Phase, 415V, 50Hz.

Table 6: Performance comparison of motors with Aluminium and copper rotors

<table>
<thead>
<tr>
<th>Motor Rating</th>
<th>Efficiency (Al) (%) / RPM</th>
<th>Efficiency (Cu) (%) / RPM</th>
<th>Difference Eff. / RPM</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.37 kW – 2 Pole</td>
<td>72.8 / 2856</td>
<td>76.1 / 2911</td>
<td>3.3 / 55</td>
</tr>
<tr>
<td>1.5 kW – 2 Pole</td>
<td>81.1 / 2926</td>
<td>82.6 / 2949</td>
<td>1.5 / 23</td>
</tr>
<tr>
<td>3.7 kW – 2 Pole</td>
<td>84.0 / 2945</td>
<td>86.8 / 2947</td>
<td>2.8 / 22</td>
</tr>
<tr>
<td>0.75 kW – 4 Pole</td>
<td>73.1 / 1442</td>
<td>74.5 / 1470</td>
<td>1.4 / 28</td>
</tr>
<tr>
<td>1.1 kW – 4 Pole</td>
<td>82.0 / 1424</td>
<td>84.5 / 1457</td>
<td>2.5 / 33</td>
</tr>
<tr>
<td>2.2 kW – 4 Pole</td>
<td>83.5 / 1411</td>
<td>85.7 / 1451</td>
<td>2.2 / 40</td>
</tr>
<tr>
<td>3.7 kW – 4 Pole</td>
<td>84.0 / 1429</td>
<td>86.9 / 1469</td>
<td>2.9 / 40</td>
</tr>
<tr>
<td>Average Efficiency improvement</td>
<td></td>
<td></td>
<td>2.37%</td>
</tr>
</tbody>
</table>

10 Pump Test Results

It could be interesting to show the contribution of CRM’s in pump industry and to observe the impact of new technology on pump performance.

Table 7: Performance comparison of 1.5 kW & 3.7kW Mono Block pump set with aluminium and copper rotors at the field

<table>
<thead>
<tr>
<th>MOTOR RATING</th>
<th>Performance Characteristics</th>
<th>Aluminium Rotor Motor Pump set</th>
<th>Copper Rotor Motor Pump Set</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5 kW, 2 Pole, Mono Block Pump set</td>
<td>Overall efficiency (%) #</td>
<td>24.5</td>
<td>26.65</td>
<td>2.15</td>
</tr>
<tr>
<td></td>
<td>Discharge (lps)</td>
<td>2.01</td>
<td>2.43</td>
<td>0.42 lps</td>
</tr>
<tr>
<td></td>
<td>Input Watts (kW)</td>
<td>2.171</td>
<td>2.413</td>
<td>0.242 kW *</td>
</tr>
<tr>
<td>3.7 kW, 2 Pole, Mono Block Pump set</td>
<td>Overall efficiency (%) #</td>
<td>30.45</td>
<td>32.84</td>
<td>2.39 %</td>
</tr>
<tr>
<td></td>
<td>Discharge (lps)</td>
<td>11.71</td>
<td>12.93</td>
<td>1.22 lps</td>
</tr>
<tr>
<td></td>
<td>Input Watts (kW)</td>
<td>3.77</td>
<td>3.86</td>
<td>0.09 kW*</td>
</tr>
</tbody>
</table>

# Under laboratory tests these pumps rendered overall efficiency levels compared to the best in industry.

* As input power is directly proportional to the cube of the speed ratios, the input power of CRM Pump set increases. Even though the input power increases, the increase in discharge reduces the operating time which in turn minimizes the Energy consumption when compared with standard Aluminium rotor motor pump sets.
By the tests on agricultural pumps we can conclude the following

(1) CRM pumps can be used for increased heads while compared to the average pumps

(2) CRM pump of same dimension can be used for superior pump range.

(3) By using CRM pump the dimension of the existing pump can be minimized.

11 Conclusion

In our short experience of design, manufacture and marketing of CRM – LT Induction motors following observations could be made.

- The cost increase in converting standard aluminium rotor motors to Eff1 level motors by using CDCR without any other design change except changes in stator winding is about 15 to 20 %

- Continuous process industries like textile mills, chemical industries, Effluent Treatment plants etc., operating 24 hours a day accepts the increase in cost as this could be got back with in 6 months of operation

- The other industries operating 8/12 hours a day are reluctant to absorb the incremental cost of higher efficiency CDCR motors.

- To be able to supply to this category of market and to satisfy all range of customers we are trying hard to design with our internal strength as well as seeking external help to modify stator configuration, body size, frame size etc., which will make the cost of CRM’s equal to or less than standard aluminium die cast rotor motors.

- When we achieve this it will be a great boon to the user industries as well as society at large through energy efficiency and energy conservation with improved technology and at affordable cost in the major area of electrical energy utilisation that is in Induction Motors.

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Potential Efficiency Gains from the Use of Electronically Commutated Motors with a High Copper Design

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Abstract
The efficiency of small conventional electric motors is poor compared with those of larger output. As fhp motors are used in large numbers, there is potential for improvements in efficiency to result in worthwhile savings. Electronically commutated (EC) motors now represent viable alternative to the traditional types of fhp electric motor.

At full load, the efficiencies of different types of EC motor tend to be similar. But the use of a slotless design of EC motor results in significantly improved efficiencies at partial load, which is often how the motor is used for the majority of the time. The design gives additional benefits such as greatly reduced noise and vibration.

The paper outlines the main features and performance characteristics of this type of EC motor, and analyses the potential net benefits on individual drive and national scales that could be expected from the widespread adoption of this type of motor.

1 Introduction
Electric motor energy efficiency programmes tend to be aimed at larger motors. This paper shows that the total potential energy saving from small motors is equally significant, due in part to the large variation in efficiency of small motors. Much of the potential saving can be achieved by using electronically-commutated (EC) motors. The „high-copper“ or „slotless“ type of EC motor is particularly efficient in service.

This paper provides a general introduction to EC motors, and then compares two different types of EC motors. A preliminary assessment of potential energy savings is undertaken; this indicates that energy efficiency programmes that concentrate on small motors are probably as important as those that deal with large motors, and that more detailed and exact studies ought to be undertaken.

2 Background
Electronically-commutated (EC) motors have the current in their windings switched by an electronic drive that is normally integrated into the motor. The rotating field produced interacts with permanent magnets in the rotor to provide the torque. EC motors are inherently more efficient at full load and rated speed than alternative motor designs, and can therefore be made smaller. This to some extent compensates for the additional bulk and cost of the electronic circuitry. EC motors are at their most competitive in the fractional and even sub-fractional horsepower regions, where three-phase squirrel-cage induction motors are generally not used.
In the fractional horsepower region, the full-load efficiency of EC motors is substantially better than that of the more conventional alternatives. Figure 1 shows typical values of full load efficiency for three different types of motor. It demonstrates the significant improvement in efficiency that is achievable by selecting an EC motor drive.

The reliability of EC motors is now comparable to that of alternative motors and drive systems, with an expected life of 45,000 running hours. In regions where the supply voltage is of variable quality, the nature of the EC motor’s built-in drive means that the motor performance and reliability are less susceptible to voltage variations than conventional motors.

![Full load efficiency graph](image)

Figure 1: Comparison of efficiencies of different types of small motor

### 3 Fractional horsepower drives

Fractional horsepower motors are sold in large numbers. A study of trade flows undertaken for the APEC Energy Working Group [Holmes, 1998] indicated that the production of small motors in Japan alone has a value of over 8,000 million US dollars, with half of that value representing motors of less than 1/10 horsepower. A more recent US study [Anon. 2003] indicated that the number of fractional horsepower motors (between 1/3 and ¾ horsepower) sold in the USA annually is of the order of 170 million.

One estimate [Green, 2004] is that motors in the approximate power range 10W to 750W constitute the largest electric motor market segment by value, and that motors in this size range are also the greatest users of electricity in aggregate. Even individual market segments can be significant. For example, in developed countries such as the
USA, around 2% of all electricity consumed is used to power electric motors used in commercial refrigerators in supermarkets, vending machines, drinks cabinets and the like. The use of high efficiency EC motors in commercial refrigerators has the potential to reduce the energy consumption of the US by around 1%, saving electricity worth about $US2 billion annually.

A previous study [de Almeida and Fonseca, 1999] indicates that fractional horsepower motors consume a much lower percentage of the total. However, that study concentrated on the industrial sector plus the tertiary sector. Many of the applications for small motors are in the commercial and domestic sectors. Even in industry, small motors often perform ancillary functions where they may be overlooked during surveys of the main processes.

**Slotless electronically commutated motors**

Not all EC motors are the same. An important variation takes full advantage of the benefits gained from having wide, shallow slots by actually dispensing with slots entirely and placing the winding in the airgap between rotor and stator. This results in a larger effective airgap, and a magnetic flux that is reduced density but with a very low harmonic content.

The difference in configuration of slotted and slotless EC motors is shown by Figure 2. Configurations with external rotors are also common for this type of motor, especially for fan drives.

![Figure 2: Indicative cross sections of conventional EC motor (left) and slotless EC motor (right) with internal rotors](image)

This design, known either as a high-copper motor or as a slotless motor, has a slightly higher copper content than a more conventional EC motor, but this is offset by a substantial reduction in the total mass of iron. A traditional salient pole machine has a complex punched lamination shape, where, for a typical 1/4hp EC machine, over 70% of the lamination raw material may be scrap after punching. However, for a slotless EC machine, the lamination form is a simple toroidal coil, with zero inherent scrap. Thus,
for similar rated machines, the manufacture of a slotless EC motor may require as little as 20% of the total lamination steel used when making a traditional EC motor.

![Graph showing comparison of efficiencies and losses for different types of EC motor](image)

**Figure 3:** Comparison of efficiencies and losses for different types of EC motor

The concentration of current in a slotless EC motor is relatively high, resulting in a motor that has the same full-load efficiency as a standard EC motor but with a higher proportion of copper losses. The slotless nature of the design means that magnetic losses associated with rapid change of flux in the teeth between winding slots are not present.

While the full-load efficiency of this design is similar to that of other EC motors, the part-load efficiency, which is where a motor generally operates for a majority of the time, is significantly improved. Figure 3 shows a comparison of efficiencies and motor losses in the common case of a motor driving a load with a “square law” characteristic.

**Typical operating pattern of fhp drives**

Generally, full output is demanded from a motor for only a small proportion of time. An earlier study [Kettner & Wurm 2003] featuring an application of EC motors indicated a distribution of demand as shown in Figure 4. Thus for the majority of the time, an EC motor could be expected to be operating in regions where a slotless EC motor has significantly lower losses than other EC motor configurations.
In the typical case of quarter horsepower motors with characteristics similar to those shown in Figure 3, the difference in total energy drawn from the supply under such an operating regime amounts to a saving of over 7%, as can be seen from Table 1.

### Table 1: A comparison of electricity consumed by different EC drives

<table>
<thead>
<tr>
<th>Speed (pu)</th>
<th>Run Time (Hours)</th>
<th>Output (W)</th>
<th>Slotless EC Motor</th>
<th>Standard EC Motor</th>
<th>Annual Energy (kWh)</th>
<th>Total annual energy use (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Total losses (W)</td>
<td>Total power (W)</td>
<td>Annual Energy (kWh)</td>
<td>Total losses (W)</td>
</tr>
<tr>
<td>1.0</td>
<td>110</td>
<td>195.0</td>
<td>60.4</td>
<td>255.4</td>
<td>28.1</td>
<td>60.3</td>
</tr>
<tr>
<td>0.75</td>
<td>440</td>
<td>109.7</td>
<td>23.2</td>
<td>132.9</td>
<td>58.5</td>
<td>27.3</td>
</tr>
<tr>
<td>0.5</td>
<td>2200</td>
<td>48.8</td>
<td>8.1</td>
<td>56.9</td>
<td>125.1</td>
<td>12.5</td>
</tr>
<tr>
<td>0.25</td>
<td>2750</td>
<td>12.2</td>
<td>3.1</td>
<td>15.3</td>
<td>42.0</td>
<td>6.0</td>
</tr>
<tr>
<td>Total annual energy use (kWh)</td>
<td>253.7</td>
<td>272.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Cost differentials and other factors

While the slotless EC machine uses slightly more copper than other EC motors, the greatly reduced use of lamination steel offsets this cost to a significant degree. However, the alternative term „high copper“ — which refers rather to the ratio of copper to iron — has been known to give potential buyers the impression that slotless motors are necessarily more expensive. Commercial confidence plus complex pricing structures make it difficult to determine actual costs. However, the impact of any additional copper cost can be weighed against reduced lifecycle energy costs.

Electricity prices are known; see for example the International Energy Agency Key World Energy Statistics 2004. The present price of copper is also easily found; see for example the London Metal Exchange listings available on the internet. From these data, and an analysis of electricity savings similar to that above, one obtains a result
that the net present value of electricity savings from selecting, say, a 160W slotless EC motor in preference to a standard EC motor is sufficient to buy a weight of copper that is over twice the total motor weight [IEA 2004; LME 2005; WDTL 2005]. Thus, the savings to be achieved are certainly many times more than enough to cover the cost of any additional copper.

As has been indicated above, the simpler configuration of the slotless type of EC motor and the reduced wastage of iron will tend to reduce manufacturing costs. This will also compensate to some extent for the greater use of copper.

Thus any cost differential due to the larger amount of copper will be covered several times over by a lower cost of manufacture plus in-service energy savings. This makes an exact analysis unnecessary in the context of this paper.

**Noise and vibration**

Due to the absence of slots, there is no slot noise, and also very little saliency torque. The use of an amorphous material for the stator eliminates magnetostrictive vibration of laminations, an effect that is often noticeable as conventional motors and other designs of EC motors age. End windings can be fully supported with a consequent reduction in vibration. These effects result in low levels of noise and vibration. Figure 5 shows the result of a comparison test between a premium external rotor induction motor and a slotless EC motor under identical conditions.

![Figure 5: Noise and vibration traces of an induction motor and a slotless EC motor](image)

In Figure 5 the peak torsional acceleration for the induction motor is 1.9G, while for the slotless EC motor the corresponding value is only 0.15G. The consistently low levels of noise and vibration make the slotless EC motor particularly suitable for domestic applications, such as heat exchange ventilation systems, extract fans, air transfer systems and the like.
4 Potential energy savings

The potential for energy savings from the adoption of slotless EC motors will obviously vary from country to country. However, it is possible to obtain an idea of the relative importance of a move to slotless EC motors in comparison with other motor-related energy efficiency initiatives.

In the case of large motors (here taken to mean those motors typically covered by mandatory minimum performance standards) the potential for energy savings from motor drives systems is on average around 24% [Cogan 1998]. Of that 24%, between 1% and 2% (i.e. up to one twelfth of the savings) is from mandatory efficiency requirements. Much of the rest is from the use of “intelligent” drives, with such measures as correct selection, installation, commissioning and maintenance accounting for the remaining savings potential. Therefore, supposing that motor drives consume, say, 20% of total electricity, the savings potential from motor drives in general is around 4.8% of total electricity consumption, while the imposition of mandatory minimum efficiency requirements contributes savings of around 0.3% of total electricity consumption.

![Energy savings potential](image)

**Figure 6**: Energy savings potential

EC motors inherently have “intelligence” built-in. However, even comparing an EC motor drive with a conventional motor with an “intelligent” drive added, the EC motor can obtain savings of around 60% [Kettner & Wurm, *op. cit.*]. As we have seen, the use of a slotless EC motors can reduce the electricity consumption by a further 7%, giving a total of 63% savings. Thus, if small motor drives currently consume half the electricity of large motor drives, that is 10% of total electricity consumption, the savings potential of using slotless EC motors is around 6.3% of total electricity consumption, with the selection of slotless EC motors in preference to ordinary EC motors contributing savings of around 0.3% of total electricity consumption.
5 Conclusions

The savings potential from small motor drives is probably at least as significant as the savings from large motor drives. In addition, the adoption of slotless EC motors could be as significant as the much-trumpeted mandatory minimum efficiency requirements for large motors. Thus the development of energy efficiency programmes aimed at improving the efficiency of small motor drives is worthy of greater consideration and some in-depth studies.

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Wellington Drive Technologies Limited: Motor technical data sheet, viewable on http://www.wdtl.com/pdf/Motors%20DD070%20WT3373_1.pdf (accessed on 23 April 2005) — Datum obtained was weight of motor = 1.4kg
Performance Characteristics of Drive Motors Optimized for Die-cast Copper Cages

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Abstract

Performance of a series of industrial drive motors designed expressly for high conductivity copper in the rotor cage is described. These motors are to replace a series of standard efficiency aluminum rotor models. Efficiencies of the copper designs meet the EFF 1 targets and are generally less expensive to build and lighter than aluminum rotor designs modeled but not built. An example of the use of MATLAB software to optimize a motor design feature, the effect of rotor skew on stray load loss, is presented.

1 Introduction

At EEMODS ’99 and ’02, results were reported from this extensive project of the world copper industry and prominent motor manufacturers to take advantage of copper in the rotor of the induction motor to increase electrical energy efficiency. A study of manufacture by high pressure die casting of the copper rotor introduced at the 1999 conference (Peters et al 1999) had been completed. This study sought to solve the problem of short die life and resulting high costs in die casting electrical grade copper with its high melting point. A nickel-base alloy die system operated at elevated temperature that had been demonstrated to greatly enhance die life was described (Peters et al 2002). Systems of this type have since been put in commercial operation to produce rotors with the copper squirrel cage. Results of motor performance tests where copper had been simply substituted for aluminum in the rotor were presented at the 2002 conference (Brush et al 2002). These results and several prior investigations from the literature showed conclusively that overall energy losses of motors with die-cast copper rotors are reduced by an average of 14% and the efficiency is increased by at least a full percentage point compared to the same motor with aluminum in the rotor. Two other papers from EEMODS ’02 also discuss manufacture of the die-cast copper rotor and performance of these motors. Parasiliti and Villani introduced the topic of redesign of the motor to increase efficiency with the copper rotor without adverse affects on starting performance (Parasiliti et al 2002). Technology for die casting copper rotors and motor performance was presented by authors from FAVI SA (Paris et al 2002).
This paper focuses on optimization of die-cast copper rotor industrial drive motors to both increase efficiency and at the same time control starting torque and in-rush current. SEW-Eurodrive has been active in an extended effort to design the motor to optimally use copper in the rotor. In April 2003, this company announced the availability of a range of EFF1 motors. Motors to 45 kW are now available. The higher efficiency had been obtained in large part by employing electrical grade copper in the rotor although stator lamination and winding designs were also modified. These modifications succeeded in raising efficiency over the entire load spectrum while at the same time maintaining torque at critical points on the torque-load curve including starting torque. Efficiency increases had to be effected without increasing the motor size to be adaptable to existing gear boxes. Using copper in the rotor allowed a reduction in frame size compared to an aluminum rotor motor of the same efficiency. Reductions in weight and manufacturing costs have turned out to be supplementary benefits of optimization for the copper rotor. This section presents results of motor performance tests by IEEE standard 112B for 1.1, 5.5, 11 and 37 kW motors and discussion of the major design considerations.

SEW employed detailed finite element modeling procedures in the optimization study. Designs employing both copper and aluminum in the rotor to achieve a given EFF1 target were carried out. Rotor slot shape to improve starting characteristics was a major focus of the design optimization of the copper rotors. Analysis of these designs using the efficient and convenient Matlab software is now underway by the MIT team to better understand the design and to test the model to see if it would predict the performance improvements actually observed. An example of MATLAB analysis on the effect of rotor skew on stray load losses is presented here.

2 Performance of copper rotor motors

Performance of copper rotor motors compared to then produced standard efficiency aluminum rotor motors is presented in this section. Design to achieve EFF 1 efficiency levels was accomplished in large part by using electrical grade copper in the rotor rather than aluminum. Rotor conductor bar shape, stator lamination and winding designs were also modified in all but the smallest (1.1 kW) motor where copper was just substituted for the aluminum. The electrical steel was upgraded from a steel with losses of 8 W/kg to 4 W/kg in all of the subject motors. These modifications succeeded in raising efficiency over the entire load spectrum while at the same time maintained torque at critical points on the torque-load curve including starting torque. Table 1 presents the test data and performance characteristics of the four motors of this study. IEEE test method 112-B was used. Standard efficiency aluminum rotor motors are compared to the improved efficiency copper rotor motors. Copper rotor motors for use at both 50 and 60 Hz were designed, built and tested. The 50 Hz machines are described in this paper. Aluminum rotor versions of the higher efficiency motors were not built because the design study showed that the copper rotor approach would generally result in lower size, weight and manufacturing costs.
Table 1: Test Data and Performance Characteristics of 1.1, 5.5, 11 & 37 kW Motors – Standard Efficiency Series Aluminum Rotor Models Compared to High Efficiency Copper Rotor Designs. 400 V, 50 Hz.

<table>
<thead>
<tr>
<th>Rotor Conductor Rated Power, kW</th>
<th>Al 1.1</th>
<th>Cu 1.1</th>
<th>Al 5.5</th>
<th>Cu 5.5</th>
<th>Al 11</th>
<th>Cu 11</th>
<th>Al 37</th>
<th>Cu 37</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated Current, A</td>
<td>2.68</td>
<td>2.45</td>
<td>11</td>
<td>10.9</td>
<td>21.8</td>
<td>21.9</td>
<td>67.1</td>
<td>67.5</td>
</tr>
<tr>
<td>Power Factor</td>
<td>0.77</td>
<td>0.79</td>
<td>0.83</td>
<td>0.83</td>
<td>0.83</td>
<td>0.81</td>
<td>0.87</td>
<td>0.85</td>
</tr>
<tr>
<td>Speed, rev./min</td>
<td>1418</td>
<td>1459.5</td>
<td>1424</td>
<td>1455.7</td>
<td>1437</td>
<td>1460</td>
<td>1468</td>
<td>1485</td>
</tr>
<tr>
<td>Rated Torque, Nm</td>
<td>7.4</td>
<td>7.21</td>
<td>36.9</td>
<td>36.15</td>
<td>73</td>
<td>71.9</td>
<td>240</td>
<td>237.7</td>
</tr>
<tr>
<td>Slip, %</td>
<td>5.50</td>
<td>2.70</td>
<td>5.10</td>
<td>2.95</td>
<td>4.20</td>
<td>2.67</td>
<td>2.10</td>
<td>1.00</td>
</tr>
<tr>
<td>Power Consumed, W</td>
<td>1435</td>
<td>1334</td>
<td>6485</td>
<td>6276</td>
<td>12590</td>
<td>12330</td>
<td>40700</td>
<td>39900</td>
</tr>
<tr>
<td>Stator Copper Losses, W</td>
<td>192.6</td>
<td>115.1</td>
<td>427.4</td>
<td>372.4</td>
<td>629</td>
<td>521</td>
<td>1044</td>
<td>975</td>
</tr>
<tr>
<td>Iron Losses, W</td>
<td>63.6</td>
<td>51</td>
<td>140.8</td>
<td>101</td>
<td>227</td>
<td>189</td>
<td>749</td>
<td>520</td>
</tr>
<tr>
<td>Stray Load Losses, W</td>
<td>9.5</td>
<td>6.7</td>
<td>100.3</td>
<td>31.4</td>
<td>163</td>
<td>171</td>
<td>699</td>
<td>200</td>
</tr>
<tr>
<td>Rotor Losses, W</td>
<td>64.1</td>
<td>31.4</td>
<td>299.2</td>
<td>170.4</td>
<td>483</td>
<td>311</td>
<td>837</td>
<td>451</td>
</tr>
<tr>
<td>Windage &amp; Friction, W</td>
<td>15.9</td>
<td>25</td>
<td>17.5</td>
<td>36</td>
<td>63</td>
<td>56.5</td>
<td>304</td>
<td>203</td>
</tr>
<tr>
<td>Efficiency, %</td>
<td>75.9</td>
<td>82.8</td>
<td>84.8</td>
<td>88.12</td>
<td>87.6</td>
<td>89.9</td>
<td>91.1</td>
<td>93.2</td>
</tr>
<tr>
<td>Temperature Rise, K°</td>
<td>61.1</td>
<td>27.8</td>
<td>80.0</td>
<td>61.3</td>
<td>75</td>
<td>62.1</td>
<td>77.0</td>
<td>70.4</td>
</tr>
</tbody>
</table>

Efficiencies of the four motors are listed in the second last line. The values increase with rated power as expected and clearly meet or exceed the EFF1 targets. Other than the rotor conductor material, the 1.1 copper rotor motor differs from its lower efficiency aluminum counterpart only in the improved grade of electrical steel used. Substantially lower rotor and iron losses result. In contrast, the high efficiency 5.5, 11 and 37 kW motors have a completely new lamination and stator design. The design modifications relate to the starting behavior discussed below. The high efficiency copper rotor motors maintain the outer motor dimensions of the aluminum versions even with the design changes including a 20 mm increase in stack height.

Table 1 lists the losses by the five categories of the IEEE 112-B test for all four motors. It is clear that, in all but the small 1.1 kW motor, the main contribution to the reduction in losses arise from reduced rotor losses. The copper rotors show losses of about 50 to 60% of that of the aluminum standard rotor motors. The two copper rotor motors at the highest power ratings have an additional stack length of about 5%. If the effect of reduced electromagnetic utilization is taken into account, the reduction is quite considerable. Since lower losses also lead to the decreased operating temperatures shown in Table 1, stator copper losses are also reduced. Lower operating temperatures suggest that the copper rotor motors will require less maintenance and have longer lifetimes.

Stray load losses (SLL) become more important with increasing power ratings amounting to about 2% of input power at 37 kW. A trend which has often been observed is that copper rotor motors exhibit lower stray load losses. This can be explained by the fact that slip is lower as well as interbar currents are suppressed. Table 1 shows that at 50 Hz, the SLL are reduced in the copper rotors for the motors of this study except for the 11 kW motor which has a rotor design leading to somewhat higher stray losses. A factor influencing SLL is bar skew. This is discussed in Section 3 below.
In industrial applications, it is quite common that drives do not run at full load at all times and partial load efficiencies must also be taken into account. Figures 1 and 2 show the dependence of efficiency on output power for the four motors at 50 Hz. Even in the partial load regime the efficiency of the copper rotor motors stays above the corresponding standard efficiency aluminum motors. Also the efficiency drop for output powers greater than 100% is smaller than it is for aluminum motors. This is due to the lower temperature rise of the high efficiency motor and therefore these motors have more thermal reserves which support good overload capabilities.

When aluminum bars are simply substituted by copper, as was the case for the 1.1 kW motor, the breakdown slip $s_b$ becomes lower since $s_b \sim R_2$. This approach leads to decreased starting torque and higher starting current. In Figure 3a, torque-speed and current-speed curves for both 1.1 kW motors are compared. The starting torque of the copper motor is 15% below that of the aluminum motor but well above two times rated torque. On the other hand, starting current is increased by about 30%. But the absolute numbers are still controllable and far from being critical. For that reason only minor design changes had been necessary for 1.1 kW motors.

The situation is different for motors of higher power rating where starting currents become more and more critical. Therefore a completely new lamination design was developed for all SEW high efficiency motors above 3 kW. The curves in Figure 3(right) display the results for the 5.5-kW motor. Again the $R_2$ effect with lower breakdown slip and steeper torque curves is obvious. But comparing the starting conditions, currents are nearly of the same magnitude, despite the lower rotor bar resistance. On the other hand the starting torque is approximately 20% lower but this was indeed a desired effect, since lower, but sufficient starting torque is beneficial for gear box life. Similar trends are seen in Figure 4 for the 11 and 37 kW motors.
Figure 3: Torque-speed and current-speed curves for the 1.1 kW motors (left) and 5.5 kW motors (right). Standard efficiency aluminium motor (blue); high efficiency copper motor (red).

Figure 4: Torque-speed and current-speed curves for the 11 kW motors (left) and 37 kW motors (right). Standard efficiency aluminium motor (blue); high efficiency copper motor (red).

As noted above, in taking the decision to use copper in the rotor for this series of industrial drive motors to reach EFF1 minimum efficiencies, SEW conducted an extensive modeling study comparing the size, weight and overall costs of motors of equivalent efficiency using aluminum in the rotor. The finding was that, for the motors discussed here, the use of copper in the rotor cage allowed reductions in rotor diameter, in iron required for laminations and in stator copper windings. The copper rotor motors are one frame size smaller than the the aluminum rotor design would have allowed. Overall there was an accompanying reduction in total manufacturing costs; the cost of the motor with an aluminum rotor at a given EFF1 efficiency ranged from similar to 15% higher than the copper version. In these examples, weight savings of up to 18% and cost savings of up to 15% were effected. This cost saving for the copper rotor motor
was in spite of the die-casting component of the copper rotor being typically three times more costly than the aluminum rotor.

Analysis by U.S. manufacturers of 7.5 and 15 Hp motors and assembled by CDA as a composite equivalent U.S. motor meeting EPAct efficiency standards came to similar conclusions. The die-cast copper rotor motors would be 18 to 20% lighter and 14 to 18% less expensive to build than the aluminum rotor motor at the same efficiency when a frame size reduction was possible. When a frame size reduction was not possible, reductions and weight and cost were still indicated in the design studies, but the percentage reductions were in the single digits for the copper rotor machine.

3 Matlab analysis of effect of rotor skew on stray load losses of the 37 kW motor

Analysis of these designs and others have been performed at MIT, using MATLAB, to understand performance improvements made possible by the use of high conductivity rotor material.

Rotors are often skewed to reduce noise and to reduce the effects of circulating currents driven by stator slot openings in rotor bars. Skew is a slight twist in the rotor so that the bars have a different angular position at one end than they have at the other. The impact of rotor skew on noise is straightforward to understand: the slot edges pass each other progressively from one end to the other so there are no sharp changes in torque because of slot edges passing. The impact on stray losses are similar; with slots skewed there are no sudden flux changes associated with slot passing that would drive circulating currents. Typically a rotor would be skewed about one stator slot pitch, so that when one rotor slot is just opposite a stator slot at one end, the other end of that slot is just opposite the next stator slot.

While skewing the rotor reduces some kinds of rotor losses it also has the effect of increasing leakage reactance and this reduces power factor. By reducing coupling between rotor and stator it also slightly increases effective rotor resistance and this has a negative impact on machine efficiency. So there tends to be an optimum value for skew.

Modeling of motor performance using the MATLAB modeling program has proved to be an effective and efficient approach and has been used here to estimate the impact of rotor skew, measured as the end-to-end angle, for the 37-kW, die-cast copper rotor motor.

As seen in Figure 5, it appears that when the rotor is insufficiently skewed, stray losses are high. If the rotor is sufficiently skewed the stray losses are low and relatively independent of skew. The estimate made here is probably low as it does not account for currents crossing through the rotor laminations.

The effect on efficiency is shown in Figure 6. As one would expect, efficiency improves as skew reduces stray loss. For higher values of skew, the main interaction becomes
Figure 5: Effect of rotor skew on stray load losses for the 37-kW copper rotor motor

Figure 6: Effect of rotor skew on motor efficiency (solid) and power factor (dashed) for the 37-kW copper rotor motor
less efficient so that efficiency falls slightly and power factor for the machine steadily decreases. This tends to limit the amount of skew one would want to use in a machine. The design of this particular machine used a skew of near one stator slot pitch. There is a power factor decrease of about 1% but the overall efficiency is near to the maximum predicted in this model.

4 References

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Energy Efficiency in Motor Driven Systems

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Abstract

In the nineties, due to the important progress in the fields of micro and power electronics, there are significant reductions in prices and sizes of frequency inverters. First, the price decrease for electronic components has opened a lot of new application fields, and, on the other hand, the decrease in sizes resulted in the development of motors with built-on frequency inverters. VEM was among the first companies that very early made this tendency out, and VEM had, from the beginning, a say in that matter. Already ten years ago, VEM presented the first series of so-called Compact Drives. The today’s product programme includes 2pole and 4pole versions in the output range from 0,55 kW up to 22 kW.

1 Preamble

VEM puts its priority on the efficiency optimisation of the whole drive system. Low-loss speed controls take only as much electric energy from the mains as the technological procedure needs. Increased losses, resulting from the operation at partial load, are avoided. VEM is thoroughly convinced that, by an optimisation of the whole technological procedure, they can make the best contribution to environmental protection and cost reduction.

By computer programmes, the amortisation times of the additional expenses for energy saving motors can be determined very exactly. But usually, the motor buyer is not identical with the user of the motors, i.e. the buyer does not pay for the energy costs and is not interested in these expenses. The plant engineering is less interested in the repay times of additional motor prices. The motors must not be expensive, must work and have to meet the required warranty periods. If, on the other hand, the whole technological process is optimised, then the plant engineering, too, is in a better sales position towards the end user. If, e.g. the consumption of hot water could be adapted to the actual requirements, then not only electric energy and water is saved, but also gas, oil or coal.

2 General features of VEM Compact Drives

Its object to put electrical drives with high-grade and cost-optimised features and adapted to the different industrial processes on the market, VEM has step-by-step approached by the development of the motor / inverter combination, i.e. the so-called Compact Drives.

These VEM Compact Drives with today’s basic technical concept are made since about 5 years. Since 2001, worth mentioning numbers of units are sold in the lower output range, and, starting with the year 2002, we succeeded also with the upper output
range. By the above-average yearly increase in sold units, also in the upper output range, we are very encouraged to have found one of the right ways to save energy.

Among the main features of VEM Compact Drives are the following:

- grey cast-iron motors
- inverters below 11 kW: aluminium housing specifically adapted to the basic motor
- inverters starting from 11 kW: sheet steel housing specifically adapted to the basic motor
- inverter housing rigidly mounted to the motor housing
- mains voltage: 380 - 415 (up to 7,5 kW: voltage up to 480 V)
- extensive modifications of inverter and motor
- as standard version: many different interfaces
  - 8 / 2 parameterable digital / analogue inputs with separated potentials
  - 2 / 2 parameterable digital / analogue outputs with separated potentials
  - 2 parameterable relay outputs

### 3 Design concept of the Compact Drives

One of the important features to be implemented by the design of Compact Drives was a robust structure and an excellent resistance against vibrations, the design aimed at the fulfilment of a large part of usual requirements made for standard motors fed by mains. From this reason, the use of standard housings for inverters was not taken into consideration.

The inverter housing is, up to an output of 7,5 kW, made of an aluminium die-cast alloy, for the larger ones the inverter is surrounded by a rigid sheet steel housing. Both versions are well adapted to the motor dimensions. Starting from the output of 11 kW, the sheet steel housings are mounted on a pair of additional motor feet, i.e. the inverter housing is without any intermediate components directly mounted to the terminal box opening of the motor housing, the contact areas are sealed in accordance to the requested degree of protection.

Due to the specific design, the control and power electronics is adapted to the new housing configuration and to the requirements for resistance against vibrations. Figure 1 shows some details of the design version for inverters in sheet steel housing.
4 Benefits of Compact Drives

Here, we will only discuss the benefits when using Compact Drives. The knowledge about general benefits of variable-speed drives are taken for granted.

(1) General benefits
- No space for control cabinets or their wall mounting required
- Due to the rigid design high resistance against vibrations
- Standard motor degree of protection (at least IP 54) for the whole assembly with the inverter included

(2) Savings in planning activities,
- No projection activities for electrical operation areas
- No inverter projection
- No projection activities for output chokes, du/dt filters, sinus filters
- No projection for cabling between motor and inverter
- No check of voltage spikes and voltage rise times at the motor terminals
- Standard version with PTC evaluation
- Standard version with radio noise suppression filters Class A (Class B as an option)
(3) Material savings
- No separate electrical operation area for the inverter
- No special insulation system because of the fact, that inadmissible voltage peaks do not arise
- No output chokes, no filters du/dt or sinus filters
- No control wires for the PTC evaluation
- No shielded motor cables (non-shielded commercially available mains connection cables are sufficient)

(4) Savings in working time due to simple mounting and connections
- No separate inverter mounting
- No cabling between motor and inverter
- No confusion of inverter input and output by mistake
- EM compatible installation at the inverter output not required

(5) Savings in working time by simple commissioning
- Drive is immediately after installation ready for operation
- Motor parameters pre-selected ex works
- No confusion for motor cables (wrong sense of rotation)
- Simple input of parameters by the parametering and operational unit, directly at site of the driven equipment, resulting in exact and quick adaptation of the inverter parameters to the technological procedures

5 Basic comparisons of motors and Compact Drives

In Table 1, there is a comparison of, for example, 2pole compact drive data with an output of 15 kW, and those of mains fed motors. It is generally well-known, that the material consumption for motors of efficiency class EFF1 is usually higher than for motors with efficiency class EFF2. A compact drive is only negligible heavier than the energy saving motor. Even if the energy saving motors have brought their high efficiency to bear, the energy savings by Compact Drives, particularly for pump applications, are significantly higher, resulting in better cost savings during operation.
Table 1: Comparison of 15 kW standard motor, 15 kW EFF1 motor and 15 kW compact drive

<table>
<thead>
<tr>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td>Weight</td>
<td>118 kg</td>
<td>140 kg</td>
<td>150 kg</td>
</tr>
<tr>
<td>Efficiency $\eta$</td>
<td>89,4%</td>
<td>91,3%</td>
<td>86,7%</td>
</tr>
<tr>
<td>Power factor of the fundamental wave</td>
<td>0,90</td>
<td>0,92</td>
<td>$\approx$ 0,99 (nominal load)</td>
</tr>
<tr>
<td>Energy saving for pump application in partial load operation</td>
<td>low</td>
<td>low</td>
<td>high (by speed reduction)</td>
</tr>
<tr>
<td>Price</td>
<td>100 %</td>
<td>$\approx$ 120 %</td>
<td>$\approx$ 460 %</td>
</tr>
<tr>
<td>Amortisation period of the additional price for 24 h operation</td>
<td>-</td>
<td>$\approx$ 3,5 months</td>
<td>$\approx$ 3 months (for average load of 60 up to 70 %)</td>
</tr>
<tr>
<td>Cost balance after 5 years of continuous operation</td>
<td>-</td>
<td>$\approx$ + 1.100 € (0,08 € / kWh)</td>
<td>up to $\approx$ + 40.000 € (0,08 € / kWh)</td>
</tr>
</tbody>
</table>

**Further criteria**

- Motor start without inrush current: no
- Additional stress for all transmission elements e.g. during motor start: high
- Electronic monitoring functions: no
- Cable cross sections for normal operational conditions: DOL: 10 mm²
- Noise reduction during partial load operation: not significant

The items listed among the „Further criteria“ show that the compact drive has additionally some very interesting advantages. It is not only the fact that cables with lower cross sections can be used, also couplings and belts are subject to lower stress. These additional cost savings are usually not included into the calculation.

6 Application fields

At this time, the main applications for Compact Drives come from the pump industries (see Figure 2). The drives are designed in such a way that, for peak load requirements, too, the pumped media are always provided in the correct amount and at the required pressure. The up-to-now usual adaptation of the drive output to the often very short-time peak loads resulted in a significantly oversized motor output for the other opera-
tional times. Therefore, the motors are, for quite some time operated in a middle or lower output range.

If the amount of transported media is decreasing, the pressure in the piping is rising, at constant motor speed. The energy savings by the use of an EFF1 motor are very low, and if there is no mechanical throttle (with high losses), the piping and fittings are subject to high stress and could be damaged. By the simple low-loss speed control of a compact drive, the process parameters can be adjusted optimally.

Figure 2: Compact Drives at site

Example (thanks to the company Grundfos)

During a day, the water consumption in a Hotel e.g. is strongly varying.

This consumption is characterised by the following:

- 100% the rate of delivery for 2 hours
- 50% the rate of delivery for 6 hours
- 30% the rate of delivery for 9 hours
- 10% of the rate of delivery for 7 hours
The water pressure could, for decreasing consumption, be controlled by a low-loss speed control of the compact drive, held at the usual level. If the delivery rate decreases to only 50 % of the projected pump output, the Compact Drive takes only 60 % of the electrical energy input of the simple motor. The energy savings run in fact up to 40 %.

If for half the flow amount, the height of delivery is decreased from 70 m to 50 m (about 70 %), the energy consumption also decreases further. Energy savings of additional 25 % compared with the operation for constant delivery height are possible.

Further fields of application are quite possible:

- Fan drives (extremely high energy savings for air conditioning)
- Compressor drives
- Belt conveyors (optimum adaptation to the technological process)

With a maximum degree of protection of IP 66, the Compact Drives up to 7.5 kW can be used in very complicated environmental conditions. The large Compact Drives fulfil the degree of protection of IP 54.

7 Profile of energy-saving products of VEM

The share of „High Efficiency“ EFF1 motors among the total motor production of VEM is in the respective output range low. As shown in Diagram 1, the number of these motors decreases slightly. At the other hand, the increase in manufactured items of Compact Drives is in the two-digit range. In the year 2004, VEM has manufactured Compact Drives about twice as much as EFF1 motors. And the trend is towards further increasing numbers. The diagram includes only Compact Drives up to an output of 22 kW, so the overall relation with respect to compact drives is still better.
8 Improved activities on the market

8.1 EFF1 motors

As shown in Diagram 1, the share of the EFF1 motors in the total motor production must be improved significantly. But, on the market, the purchase of more expensive motors has not succeeded, despite of the cost savings during operation.

The car industry e.g. does not know such problems. On that field, the customers know, without any additional training, which engine is cost-saving for the respective operational conditions. For the more expensive, but energy-saving Diesel engines, the growth rates were significant.

Why does the share of energy saving electric motors not grow in the same way? The problem for the rise of market shares for EFF1 motors bases on the fact, that normally the buyers are not the users of motors. If that enterprise or person that pay for the electricity bill, do not request energy saving motors, then the plant projecting engineers, from their economic reasons do not plan energy saving drives. Also very sophisticated motor developments and computer programmes would not at all change the situation, because normally the motor manufacturer has no direct contact with the end-user.

This situation would not change basically as long as the rating of low investment expenses is better than that of low energy expenses.

To try to change the situation, not only projecting and planning engineers, but also the end-users of plants must be better informed and take more care of the chances to save
money by the use of EFF1 motors. We have to repeat again and again that the purchase price of a motor is very low compared with the operational cost. The price makes maximum 3% of the lifecycle cost of, e.g. 12 years motor operation. 97% of the total cost are due to motor operation and maintenance.

If, for a specific customer, the use of energy saving motors had success, then it could happen that he goes to the other extreme. For all motors in a plant, EFF1 motors are demanded. In some specifications, there is no difference in operation time and kind of duty. If EFF1 motors are used in short-time or intermittent duty, the expected amortisation fails. The energy savings are very low, and the higher expenses for the motors, arising from the increased material cost, are not at all compensated for by this kind of use.

### 8.2 Compact Drives

Compact Drives have, compared with standard variable speed drives, definitely lower prices. The compact drive is a complex and ready-for-use product. It has, in its standard version, all important components included, and, from its principle, further expensive devices are not necessary.

In the configuration with separated motor and inverter, additional expenses arise at the different sub-suppliers. The sub-suppliers are responsible for the electrical planning, the switchgear and the electrical installation. They are also responsible for the procedure to combine the different components, i.e. the EMC filters, the output chokes, the output filters, the shielded cables etc., to a well-functioning drive system.

If the customer does not specify Compact Drives expressly, then the project planning enterprises do not use them. The separate design of all components is in every case more expensive, but the financial extra cost are not taken into account. The project planning enterprise purchases only the most cost-effective components standard motor and standard inverter. These components are then, by the subcontractors of the project planning enterprise, combined to a functioning drive. The additional expenses are unhesitatingly accepted.

The significant price advantage of Compact Drives is up to now, on a large scale, only accepted by the pump manufacturers. Most of the other industrial branches are more sparing in the use of Compact Drives. Using a compact drive, the pump manufacturers are responsible for the whole installation procedure. The arising expenses must be taken by the own enterprise, the shifting to other subcontractors makes no benefits.

### 9 Further development trends at VEM

Due to the positive experience with respect to VEM Compact Drives in the last few years, the widening of the output range up to 45 kW and the extension of the voltage range up to 500 V is planned.
This is one of the steps to meet the expectations for high-grade energy-saving drive solutions. By additional optional features of motor / inverter combinations, further fields of application could be opened, and approvals by well-known authorities will promote the world-wide sale.

For all fields of application, where the use of motors with constant speed in continuous duty is useful, VEM will also in the future make all efforts to promote EFF1 motors. But for further developments, the optimum relation between expenditures and benefits for the environment will be taken into account.

10 References

1. Grundfos Presentation „Water requirements in a hotel“
Efficiency Measurements
The Eh-star Method for Determination of Stray Load Losses in Cage Induction Machines

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Abstract

The eh-star-circuit is an asymmetric feeding of a three-phase induction machine to measure the stray load losses without coupling of the machine and without needing any dynamometer. The theoretical background of this method is discussed and the influence of different parameters on the stray load losses is investigated. The measurement procedure for eh-star method is described in detail. This work was funded by a CEMEP working group. Fourteen motors (2-, 4- and 6-pole) with current design of six European manufacturers with rated power 5.5 kW and 11 kW are investigated. The stray load losses are determined with three experimental measurement procedures: input-output method B, and reverse rotation test (RRT), acc. to the American standard IEEE 112-1996, and eh-star-circuit. RRT method gives bigger stray load losses by factor 2, whereas method B and eh-star-circuit results correlate quite well.

1 Introduction

Stray load losses contribute in standard cage induction machines to typically 0.5...3% of electrical machine power, resulting from eddy currents in conductive parts due to harmonic field components, inter-bar currents and current displacement effects (see Oberretl 1969). Measurement of stray load losses with input-output test (see IEEE 112-1996) needs calibrated measurement device for electrical and mechanical machine power and a coupled load (see Boglietti et al. 2004). Investigations of stray load losses for fourteen motors of six European manufacturers were done during a CEMEP research project, looking also for simple and cheap alternative tests to assess stray load losses. The eh-star-circuit was found, which is an asymmetric feeding of a three-phase induction machine (squirrel cage or wound rotor) like in the Steinmetz circuit (see Jordan et al. 1967). The eh-star-circuit method is well-suited for determination of stray load losses in manufacturer test bays without coupling of the machine and without needing any dynamometer. One needs in addition to measurement results in eh-star circuit with external resistance, the measurement of stator resistance and temperature and measurement results of no-load test (friction and iron losses).

2 Eh-star-circuit: Test procedure and computation

The conditions of eh-star test can be summarized as:

- Feeding of machine with asymmetrical 3-phase current system, which consists mainly of inverse field component $I_{s,2}$ (= negative sequence current component).
Efficiency Measurements
The Eh-star Method for Determination of Stray Load Losses in Cage Induction Machines

- Rotor speed should be near synchronous speed (e.g. near rated speed is sufficient), so that slip of inverse field is nearly \( s = 2 \). So inverse field rotates with \( s_2 = (2 - s) \approx 2 \) like at reverse rotation test RRT (see IEEE 112-1996), but without need of coupling the machine with dynamometer.

- Rotor current of inverse system at \( s \approx 2 \) simulates load condition as at RRT. So only stray load losses due to \( I_{s,2} \) are considered for final result.

- Positive sequence component \( I_{s,1} \) shall be small, so that decomposition of total stray load losses, measured at asymmetric circuit, into positive and negative sequence component, do not influence much the final result.

The machine stator winding has to be connected in star. So rated machine data are referred to star connection. The star-point must not be connected to avoid zero-sequence currents. Before starting the test the machine should have run already for certain time to get stable no-load losses. Motor is started in star connection at no load in symmetric operation at reduced voltage (e.g. at 25% ... 40% of rated voltage) up to about synchronous speed. After start-up phase W is disconnected from grid via switch and an ohmic resistance \( R_{eh} \) is put between phase U and W (Figure 1a). This resistance should be about short circuit impedance of the motor, which is typically 20% of rated impedance (\( R_{eh} = 0.2 \cdot U_{N,ph} / I_{N,ph} \)) and shall be adjusted, so that the positive sequence current \( I_{s,1} \) stays below 30% of negative sequence current \( I_{s,2} \) and the speed stays in the range of typical motor speed near rated speed. Hence the motor is fed between U and V with reduced voltage at rated frequency with about rated speed. During the test the supply voltage shall vary for at least six test points. The test points shall be chosen to be approximately equally spaced between 150% and 75% of rated phase current measured in phase V (\( I_V \)). When starting the test one should begin with the highest current and proceed in descending order to the lowest current. Due to the asymmetric feeding the three phase currents are different, with typical values between 130% ... 70% of average value. The decomposition of the 3 currents into pos. seq. and neg. seq. current yields in that case about 25% positive and 100% negative sequence current. As the negative sequence dominates, the machine may be assumed to be mainly operating under inverse field conditions, similar to the RRT. Decomposing the total measured losses (without losses in \( R_{eh} \)) into iron, friction and pos. and neg. seq. stator copper and rotor cage losses, the remaining negative sequence losses are the stray load losses, corresponding to slip \( s \approx 2 \). Thus these losses should be nearly the same as at the same current under reverse rotation test conditions, but without needing any dynamometer. A second advantage of eh-star-circuit in comparison to RRT is the fact, that the positive sequence current system of about 25% ... 30% of negative sequence current excites a main flux of about the same order, which resembles more the full flux operation at rated slip than the RRT does. So one may expect that the measured stray load losses of eh-star-circuit are closer to input-output results of method B (see IEEE112-1996) than the RRT results. Another advantage of eh-star-circuit in comparison to RRT is, that no removed rotor test is necessary, because stray load losses are evaluated directly by load flow calculation from T-equivalent circuit, including stator stray load losses and iron losses (Figure 1b).
The total additional losses at asymmetrical feeding $P_{ad,asym}$ are the sum of additional losses of positive $P_{ad,1}$ and negative $P_{ad,2}$ sequence system

\[
P_{ad,asym} = P_{ad,1} + P_{ad,2} = (1 - s) \cdot (P_{\delta 1} - P_{\delta 2}) - P_{fe},
\]

For determination of additional losses of asymmetrically fed machine the friction and windage losses $P_{lw}$ and the difference of air gap power of positive $P_{\delta 1}$ and negative $P_{\delta 1}$ sequence machine are needed. Friction and windage losses we get from no-load test. For determination of air gap power (internal power) the iron losses $P_{Fe,s}$ and stator resistance $R_s$ must be known in addition. The measurements to get these values are regularly done at each test bay during motor type test. The air gap power is given as

\[
P_{\delta} = 3 \cdot \text{Re}\left(\frac{U_{sl}}{L_{sl}}\right) = P_{e,in} - P_{Cu,s} - P_{Fe,s},
\]

where $U_{sl} = U_s - I_s \cdot R_s$

is the voltage drop (inner voltage) at the iron resistance (Figure 1b), and

\[
L_{sl} = L_s - L_{s,Fe}
\]

is the inner current, the current "behind" the iron resistance (Figure 1b).

The air gap power of positive and negative sequence system are:

\[
P_{\delta 1} = 3 \cdot \text{Re}\left(\frac{U_{sl,1}}{L_{sl,1}}\right), \quad P_{\delta 2} = 3 \cdot \text{Re}\left(\frac{U_{sl,2}}{L_{sl,2}}\right),
\]

the positive and negative sequence components of the inner phase voltage are

\[
U_{sl,1} = \frac{1}{3} \left( U_{Li} + a \cdot U_{Vl} + a^2 \cdot U_{Wl} \right), \quad U_{sl,2} = \frac{1}{3} \left( U_{Li} + a^2 \cdot U_{Vl} + a \cdot U_{Wl} \right),
\]

the positive and negative sequence components of the inner phase current are

\[
I_{sl,1} = \frac{1}{3} \left( I_{Li} + a \cdot I_{Vl} + a^2 \cdot I_{Wl} \right), \quad I_{sl,2} = \frac{1}{3} \left( I_{Li} + a^2 \cdot I_{Vl} + a \cdot I_{Wl} \right).
\]
The torque $M$ is proportional to slip $s$ and proportional to rotor current (load current) $I'_r$ in the linear range of the $M$-$s$-characteristic between no-load ($s = 0$) and typically twice rated slip ($2s_N$), Figure 2a. So the equivalent of torque $M$ of uncoupled machine may be the rotor current $I'_r$, which ranges between $0...I'_{rN}$ for $M = 0,...,M_N$: $M \sim I'_r$. The load current $I'_r$ at eh-star test corresponds, due to the slip $s \approx 2$, to the neg. seq. current $I_{s,2}^2$: $I_r \approx I_{s,2}^2$. So the negative sequence system represents the equivalent motor load of the uncoupled machine. Hence the additional losses of the negative sequence system $P_{ad,2}$ are the stray load losses of an equivalent symmetrically fed machine. Assuming stray load losses depending on square of torque $M^2$ or rotor current $I_r^2$, which for $s \approx 2$ is also stator current $I_{s,2} \approx I'_r \sim M$, we get with $P_{ad,2} \sim I_{s,2}^2$ and $P_{ad,1} \sim I_{s,1}^2$:

$$P_{ad,2} = P_{ad,asym} \cdot \frac{I_{s,2}^2}{I_{s,1}^2 + I_{s,2}^2} = P_{ad}$$

The additional losses $P_{ad,N}$ of a symmetrically fed machine at rated operation are

$$P_{ad,N} = P_{ad,asym} \cdot \frac{I_{s,N}^2}{I_{s,1}^2 + I_{s,2}^2}.$$  

(12)

Figure 2: a) Torque-slip-characteristic b) Phasor diagram of induction machine

From phasor diagram (T-equivalent circuit Figure 1b) for motor operation we get the rated test current $I_{Nt}$. With the assumption of right angle between $I_{mN}$ and $I'_r$ (Figure 2b) the rated test current $I_{mN}$ is determined from rated current $I_{sN}$ and rated no-load current $I_{s0}$ as

$$I_{mN} = \sqrt{I_{sN}^2 - I_{s0}^2}.$$  

(13)
As rated torque is proportional to rated rotor current, we get $M_N \sim I'_{cN}$

$$I'_{cN} \cong \sqrt{I^2_{sN} - I^2_{s0}} = I_{nN},$$ (14)

and we can plot the stray load losses $P_{ad,2} = P_{ad}$ vs. square of ratio of negative sequence current related to rated test current, which corresponds to square of per unit torque $(I_{s,2}/I_{N})^2 = (M/M_N)^2$ (Figure 2a). The stray load losses data shall be smoothed by using the linear regression analysis. The offset must be omitted, as at zero torque, which corresponds with zero load current and hence zero negative sequence current, the stray load losses shall be zero. The stray load losses for rated load $(I_{s,2}/I_{N} = 1)$ are the slope of straight line of regression.

![Figure 3: Measured stray load losses acc. to eh-star for test motor B132-6](image)

### 3 Influence of motor design on stray load losses

The stator slot harmonics due to the stator current $I_s$ with frequency $f_s$ induce the rotor cage. The harmonic rotor currents cause additional losses in rotor cage and as interbar currents in the stack. This is an essential part of stray load losses.

$$B_{s,v}(x, t) = B_{s,v} \cdot \cos(v \cdot \frac{x \cdot \pi}{\tau_p} - \omega t), \quad v = 1 + 6 \cdot g, \quad g = 0, \pm 1, \pm 2, ...$$ (15)

$\tau_p$ is pole pitch, $v$ are the ordinal numbers of stator harmonics. The dominating slot harmonics are calculated as:

$$v_Q = 1 + (Q_s/p) \cdot g.$$ (16)

The rotor slot harmonics due to rotor current $I_r$ with rotor frequency $f_r = s \cdot f_s$ induce the stator winding and cause additional losses in stator, which also form a part of SLL.
\[ B_{r,\mu}(x_r,t) = B_{r,\mu} \cdot \cos(\mu \cdot \frac{x_r}{\tau_p} - s \cdot \omega t), \quad \mu = 1 + \left( \frac{Q_r}{p} \right) \cdot g \]  

\( \mu \) are the ordinal numbers of rotor slot harmonics. Stator harmonic currents \( I_{s\mu} \) are induced by rotor slot harmonics with frequency \( f_{s\mu} = f_s \cdot \left[ \mu \cdot (1 - s) + s \right] \). At load \((s = s_N)\) the rotor current \( I_r \) causes stator harmonic currents. At symmetric feeding of no-load \((s = 0)\) the fundamental rotor current \( I_r \) is zero, so no stator harmonic currents occur. In Table 1 the measured harmonic currents factor (HCF) acc. to IEC 60034-1 during eh-star test is mainly determined by the above noted stator harmonic current \( I_{s\mu} \). The bigger the slotting influence in a machine, the bigger the slot harmonic fields and hence the HCF and the stray load losses. The slot harmonic amplitudes \( B_{s,\nu Qs} \) and \( B_{r,\nu \mu} \) are calculated with the influence of winding parameters, slot numbers \( Q_s, Q_r \) and slot openings \( s_Qs, s_Qr \) acc. to theory (see Binder 1988). The first pair of slot harmonics for stator and rotor is given. For closed rotor slots an equivalent slot opening \( s_{Qr,eq} \) is used.

Table 1: Influence of motor design on stray load loss

<table>
<thead>
<tr>
<th></th>
<th>A160-4</th>
<th>B160-4</th>
<th>C160-4</th>
<th>D160-4</th>
<th>E160-4</th>
</tr>
</thead>
<tbody>
<tr>
<td>HCF [%]</td>
<td>eh-Y</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P_{st,eh}/P_N</td>
<td>1.26%</td>
<td>0.93%</td>
<td>0.95%</td>
<td>1.16%</td>
<td>2.25%</td>
</tr>
<tr>
<td>Q_s/Q_r</td>
<td>48/40</td>
<td>36/28</td>
<td>48/40</td>
<td>48/36</td>
<td>36/28</td>
</tr>
<tr>
<td>s_{Qs}/\delta, s_{Qr,eq}/\delta</td>
<td>3.1, 3.3</td>
<td>6.6, 2.7</td>
<td>5.6, 2.7</td>
<td>7.0, 3.8</td>
<td>8.6, 4.6</td>
</tr>
<tr>
<td>B_{s1} [T]</td>
<td>0.91</td>
<td>0.81</td>
<td>0.9</td>
<td>1.0</td>
<td>0.93</td>
</tr>
<tr>
<td>\nu_{Qs}</td>
<td>-23, +25</td>
<td>-17, +19</td>
<td>-23, +25</td>
<td>-23, +25</td>
<td>-17, +19</td>
</tr>
<tr>
<td>B_{s1,Qs} [T]</td>
<td>0.2 / 0.045</td>
<td>0.4 / 0.19</td>
<td>0.35 / 0.21</td>
<td>0.47 / 0.3</td>
<td>0.59 / 0.29</td>
</tr>
<tr>
<td>\mu</td>
<td>-19, +21</td>
<td>-13, +15</td>
<td>-19, +21</td>
<td>-17, +19</td>
<td>-13, +15</td>
</tr>
<tr>
<td>B_{r1} [T]</td>
<td>0.18 / 0.018</td>
<td>0.19 / 0.06</td>
<td>0.18 / 0.018</td>
<td>0.2 / 0.002</td>
<td>0.32 / 0.04</td>
</tr>
</tbody>
</table>

Slot harmonic amplitudes increase with decreased ratio of “slot number /pole” and with increased ratio of “slot opening/air gap”. Skewing shall reduce harmonic voltage induction, but increases inter-bar currents. This causes additional losses in rotor. At motor A160-4 with the lowest harmonic amplitudes and small skewing the stray load losses are small. At motor E160-4 with small air gap and low slot number the slot harmonic amplitudes and the stray load losses are bigger. The measured HCF is therefore higher due to increased slot harmonic amplitudes and so are the measured stray load losses with eh-star method. So the influence of motor design on stray load loss is well shown by the eh-star measurement.
4 Influences of measurement parameters on eh-star results

4.1 Influence of eh-resistance on pos. and neg. sequence system

The positive and negative sequence impedances are calculated as:

\[ Z_1 = Z(s) = Z_{1,se} + j \cdot Z_{1,im}, \quad Z_2 = Z(2 - s) = Z_{2,se} + j \cdot Z_{2,im} \] (18), (19)

with

\[ Z(x) = R_s + jX_s, R_{Fe}, \quad \frac{R'_e + j \cdot x \cdot \alpha X'_r}{(R_{Fe} R'_e - x \cdot \alpha X_s X'_r) + j \cdot (x \cdot R_{Fe} X'_r + X_s R'_e)} \] (20)

with leakage coefficient \( \sigma = 1 - \frac{X'_b}{X_s X'_r} \) and reactances \( X_s = X_{s,\sigma} + X_b, \quad X'_r = X'_{r,\sigma} + X_b \).

The impedances depend on slip \( s \), which is determined during eh-star test by load (friction losses), by stator voltage \( U_{UV} \) and by resistance \( R_{eh} \).

The positive and negative sequence currents are calculated as:

\[ L_{1,2} = \frac{U_{UV}}{3} \cdot \frac{(1 - a^2) \cdot R_{eh} - 3a^2 \cdot Z_2}{3 \cdot Z_s Z_2 + R_{eh} \cdot (Z_1 + Z_2)}, \quad L_{1,2} = \frac{U_{UV}}{3} \cdot \frac{(1 - a^2) \cdot R_{eh} - 3a^2 \cdot Z_2}{3 \cdot Z_s Z_2 + R_{eh} \cdot (Z_1 + Z_2)}, \quad a = e^{\frac{2\pi}{3}} \] (21, 22)

Figure 4a gives calculated pos. and neg. sequence voltage by variation of \( R_{eh} \) with the assumption, that the slip and voltage \( U_{UV} \) are constant. Figure 4b shows the calculated pos. and neg. sequence current for a small (11 kW) and a big (1 MW) 4-pole motor at constant rated slip and voltage \( U_{UV} \). Of course in reality slip is not constant, as with varying current the electromagnetic torque varies, too, which has to balance load torque due to friction, windage and stray load losses. The varying slip was taken from measurement for 11 kW, 4-pole motor and used for calculation in Table 2 and Figure 5.

![Figure 4: Influence of \( R_{eh} \)-resistance on calculated positive and negative sequence system, a) Voltage b) Current (\( Z_{sc} \): short circuit impedance)](image-url)
This calculated influence of varying slip on positive and negative sequence currents with a comparison to measurement for 11 kW, 4-pole motor is given in Table 2.

Table 2: Influence of $R_{eh}$-resistance on positive and negative sequence system, comparison measurement and calculation, motor E160-4

<table>
<thead>
<tr>
<th>$R_{eh}$ [Ohm]</th>
<th>5.3</th>
<th>3.7</th>
<th>2.5</th>
<th>1.3</th>
<th>1.15</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{eh} / Z_{sc}$</td>
<td>2.12</td>
<td>1.48</td>
<td>1.0</td>
<td>0.52</td>
<td>0.46</td>
</tr>
<tr>
<td>Speed [1/min]</td>
<td>1483.2</td>
<td>1468.7</td>
<td>1451.3</td>
<td>1422.2</td>
<td>1387.8</td>
</tr>
<tr>
<td>$I_{s,1} / I_{s,2}$ measured</td>
<td>0.19</td>
<td>0.21</td>
<td>0.248</td>
<td>0.29</td>
<td>0.40</td>
</tr>
<tr>
<td>$I_{s,1} / I_{s,2}$ calculated</td>
<td>0.158</td>
<td>0.207</td>
<td>0.251</td>
<td>0.32</td>
<td>0.40</td>
</tr>
</tbody>
</table>

At small $R_{eh}$, the small positive sequence voltage $U_{s,1}$ leads to small torque $M_1 \sim U_{s,1}^2$, so to big slip due to friction load, hence increasing positive sequence current $I_{s,1}$, so the ratio $I_{s,1} / I_{s,2}$ increases. If $R_{eh}$ increases to large values, the positive sequence voltage increases, so the slip decreases to zero. The negative sequence voltage decreases significantly and so does $I_{s,2}$, hence the ratio $I_{s,1} / I_{s,2}$ increases again. At infinite $R_{eh}$ the ratio $I_{s,1} / I_{s,2} = 1$, so there exists a value $R_{eh}^*$ where the ratio $I_{s,1} / I_{s,2}$ is minimum (Figure 5), which is the optimum for eh-star.

Figure 5: Influence of $R_{eh}$-resistance on pos. and neg. sequence system, comparison of measurement for 5.5 kW & calculation for 11 kW 4-pole motors
4.2 Influence of $R_{eh}$ -resistance on measured stray load losses

The influence of $R_{eh}$-resistance on measured stray load losses by small variation of $R_{eh}$ is not big (Table 3), as long as $I_{s,1}/I_{s,2}$ is sufficiently small (< 0.3).

Table 3: Influence of $R_{eh}$-resistance on measured stray load losses for 2-pole motor

<table>
<thead>
<tr>
<th>Measured motor 11 kW</th>
<th>A160-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{eh}$ [Ohm]</td>
<td>14.2</td>
</tr>
<tr>
<td>Pos. sequence current / $I_{In}$</td>
<td>0.29</td>
</tr>
<tr>
<td>Neg. sequence current / $I_{In}$</td>
<td>1.00</td>
</tr>
<tr>
<td>Stray load losses [W]</td>
<td>208</td>
</tr>
<tr>
<td>Variation [%]</td>
<td>-</td>
</tr>
<tr>
<td>Speed [1/min]</td>
<td>2932</td>
</tr>
<tr>
<td>Winding temperature [°C]</td>
<td>52</td>
</tr>
</tbody>
</table>

4.3 Influence of temperature on stray load losses

In phase V flows maximum current during asymmetric eh-star test, in phase U flows medium current and in phase W flows minimum current. This leads to different heating of the three phase resistances. The colder the winding, the less the error due to influence of unequal heating of the three phases. Average value of hottest (V) and coldest (W) phase resistance leads to “average” temperature rise for calculating stator winding resistive losses! So line-to-line resistance between terminals V and W is used.

Table 4: Influence of temperature on stray load losses at rated load ($I_{s,2}/I_{In} = 1$)

<table>
<thead>
<tr>
<th>Motor E160-4</th>
<th>A: “cold”</th>
<th>B: “Warm”</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winding temperature</td>
<td>55.3 °C</td>
<td>85.9 °C</td>
</tr>
<tr>
<td>Pos. Sequence phase current / $I_{In}$</td>
<td>0.22</td>
<td>0.23</td>
</tr>
<tr>
<td>Stray load losses [W]</td>
<td>248</td>
<td>346</td>
</tr>
<tr>
<td>Variation B / A</td>
<td>39%</td>
<td></td>
</tr>
</tbody>
</table>

The influence of temperature on stray load loss measurement is significant at hot motor, because the different heating of the three phases deviates much more from the assumed average value as for “cold” machine. To avoid this error, one should measure all three phase resistances separately for each test point. As this is too much effort for economic test procedure, only hottest and coldest phase resistance are measured at the beginning and end of test. For load points in between interpolation is used.
5 Stray load losses of eh-star test for different motors

The measured stray load losses of eh-star method at rated load ($I_{s,2}/I_{N} = 1$) are presented for different pole counts of 11 kW and 5.5 kW motors in Table 5.

Table 5: Eh-star measurement data at rated load ($I_{s,2}/I_{N} = 1$)

<table>
<thead>
<tr>
<th>11 kW 4-pole motors</th>
<th>A160-4</th>
<th>B160-4</th>
<th>C160-4</th>
<th>D160-4</th>
<th>E160-4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pos. sequence current / $I_{N}$</td>
<td>0.23</td>
<td>0.24</td>
<td>0.28</td>
<td>0.22</td>
<td>0.22</td>
</tr>
<tr>
<td>Stray load losses [W]</td>
<td>139</td>
<td>102</td>
<td>105</td>
<td>128</td>
<td>248</td>
</tr>
<tr>
<td>Speed [1/min]</td>
<td>1462</td>
<td>1474</td>
<td>1452</td>
<td>1475</td>
<td>1466</td>
</tr>
<tr>
<td>Winding temperature [°C]</td>
<td>54</td>
<td>45</td>
<td>52</td>
<td>46</td>
<td>55</td>
</tr>
<tr>
<td>Pos. sequence current / $I_{N}$</td>
<td>0.23</td>
<td>0.21</td>
<td>0.19</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>Stray load losses [W]</td>
<td>210</td>
<td>102</td>
<td>109</td>
<td>501</td>
<td></td>
</tr>
<tr>
<td>Speed [1/min]</td>
<td>2956</td>
<td>2957</td>
<td>2980</td>
<td>2963</td>
<td></td>
</tr>
<tr>
<td>Winding temperature [°C]</td>
<td>78</td>
<td>50</td>
<td>56</td>
<td>49</td>
<td></td>
</tr>
<tr>
<td>5.5 kW 4- &amp; 6-pole motors</td>
<td>A132-4</td>
<td>A132-6</td>
<td>B132-6</td>
<td>C132-6</td>
<td>D132-6</td>
</tr>
<tr>
<td>Pos. sequence current / $I_{N}$</td>
<td>0.28</td>
<td>0.26</td>
<td>0.34</td>
<td>0.27</td>
<td>0.26</td>
</tr>
<tr>
<td>Stray load losses [W]</td>
<td>111</td>
<td>66</td>
<td>173</td>
<td>58</td>
<td>40</td>
</tr>
<tr>
<td>Speed [1/min]</td>
<td>1413</td>
<td>981</td>
<td>979</td>
<td>968</td>
<td>975</td>
</tr>
<tr>
<td>Winding temperature [°C]</td>
<td>59</td>
<td>42</td>
<td>41</td>
<td>44</td>
<td>43</td>
</tr>
</tbody>
</table>

6 Comparison of different measurement methods

The comparison of measured stray load losses with three different methods is presented in Table 6. The RRT method (IEEE112-1996) gives bigger stray load losses by the factor of 2, whereas the eh-star stray load losses correlate better with the results of input-output method B (IEEE112-1996).

Table 6: Measured stray load losses from different methods

<table>
<thead>
<tr>
<th>11 kW 4-pole motors</th>
<th>A160-4</th>
<th>B160-4</th>
<th>C160-4</th>
<th>D160-4</th>
<th>E160-4</th>
</tr>
</thead>
<tbody>
<tr>
<td>RRT/ Method B</td>
<td>1.53</td>
<td>1.09</td>
<td>1.21</td>
<td>2.03</td>
<td>1.72</td>
</tr>
<tr>
<td>Eh-star/ Method B</td>
<td>1.01</td>
<td>0.7</td>
<td>0.62</td>
<td>0.85</td>
<td>1.03</td>
</tr>
<tr>
<td>RRT/ Method B</td>
<td>1.27</td>
<td>1.18</td>
<td>1.49</td>
<td>1.18</td>
<td></td>
</tr>
<tr>
<td>Eh-star/ Method B</td>
<td>0.87</td>
<td>0.7</td>
<td>1.14</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>5.5 kW 4- &amp; 6-pole motors</td>
<td>A132-4</td>
<td>A132-6</td>
<td>B132-6</td>
<td>C132-6</td>
<td>D132-6</td>
</tr>
<tr>
<td>RRT/ Method B</td>
<td>1.54</td>
<td>2.39</td>
<td>1.59</td>
<td>3.17</td>
<td>1.53</td>
</tr>
<tr>
<td>Eh-star/ Method B</td>
<td>0.73</td>
<td>1.34</td>
<td>1.14</td>
<td>1.45</td>
<td>0.92</td>
</tr>
</tbody>
</table>
7 Conclusion

The stray load losses were measured with input-output method B and with reverse rotation test (IEEE 112-1996) and with eh-star-circuit. The experimental evaluation of 5.5 kW and 11 kW motors with pole count 2, 4 and 6 showed good coincidence between input-output method B and the eh-star circuit. Thus the eh-star method seems to be a good, lower cost alternative for determination of stray load losses of induction machines. The eh-star-circuit method is simple and well suited for determination of stray load losses in manufacturer test bays without coupling of the machine and without needing any dynamometer. One needs measurement results in eh-star circuit with external resistance, measurement of stator resistance and temperature and measurement results of no-load test (friction and iron losses). The influence of different parameters on the stray load losses was shown, the most critical is motor temperature.

8 References


Converting Energy Efficiency Requirements to Account for Different Test Protocols

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Abstract

IEC 60034-2 and IEC 61972 give different results when determining the losses and efficiencies of cage induction motors. The latter is of greater interest to users and to those implementing energy efficiency programmes. But motor efficiency requirements may still be expressed in terms of the IEC 60034-2 test protocol. The Australian and New Zealand minimum efficiency requirements for induction motors have separate but parallel sets of minimum efficiency requirements so that either test protocol can be used to demonstrate compliance (or otherwise). For this Standard the author devised a method of calculating equivalent efficiency requirements. The conversion method makes certain assumptions and uses these to recalculate the modified efficiency values used as the requirements for motors tested to the alternative protocol. Experience indicates that in practice the relationship between them corresponds to the results obtained by testing to the different test protocols.

1 Background

Around 1998, Australia and New Zealand were in the position of wishing to proceed with the development of mandatory minimum efficiency requirements for three-phase cage induction motors. But there was the problem of which test protocol to use. IEC 34-2 (as it was still known then) was still the existing standard in use in most countries with a 50Hz supply, but since the first EEMODS conference in 1996 it was generally acknowledged that a test protocol akin to IEEE 112 provided results that were both more consistent and that were more representative of efficiencies experienced in service. Work on this new standard, IEC 61972 had started, but was proceeding slowly (Glew). It was, however, definitely the “standard of the future” and for a long-term energy efficiency programme the working group developing the Australian and New Zealand requirements considered it to be the right test protocol to use. On the other hand, those then supplying the Australian and New Zealand markets were using the IEC 34-2 test protocol.

Another factor to be considered was the minimum efficiency levels to be specified. Despite the large geographic area covered, Australia and New Zealand combined are still only a small market by world standards, and therefore the pragmatic decision was taken to try to align requirements with those of other countries where feasible and appropriate.
2 Development of a translation algorithm

2.1 Concept

It was realized these problems could be solved if it were possible to relate the results of testing in accordance with IEC 34-2 to the results of testing the same machine to IEC 61972. The biggest discrepancy was in the determination of additional (or stray) losses. In IEC 61972 these are determined via test measurements; in IEC 34-2 they are allocated a value of 0.5% of input. The actual value is highly variable.

The draft of IEC 61972 that was being used as a model for the Australian and New Zealand Standard included an option for allocating additional losses. The allocation ranged from 3% of input for motors of less than 1kW rated output via 1.5% for 200kW motors down to 0.5%. This curve is shown as the solid line in Figure 1. Note that this is different from that in later drafts and the published version of the IEC standard which is the broken line in the figure.

![Figure 1: Allocation of additional losses](image)

This allocation is not an average, but was chosen to be pessimistic for the great majority of motors. The reasoning was that if a manufacturer thought the allocation was too disadvantageous to a particular motor design, it could always be tested to the alternative method and have the actual additional losses determined via measurement.

Clearly it was not reasonable to expect it to be possible to develop a translation algorithm that could be applied to individual motors with any degree of rigorous accuracy. But it was realized that it was possible to develop an algorithm for use when setting...
minimum efficiency requirements on the principle that: “A motor that passes when tested to IEC 34-2 or equivalent standard should usually also pass when tested in accordance with AS/NZS 1359.2.3 or other standard equivalent to IEC 61972.”

Minimum efficiency requirements could then be set equivalent to recognized requirements for motors tested to the old standard. When the requirements of the energy efficiency programme became mandatory, it would be possible to accept test results from tests carried out to either test protocol.

2.2 Algorithm

The following considerations applied when developing the translation algorithm:

- Additional losses would be more under the new test regime, and this would be the main adjustment.
- IEC 34-2 adjusts copper losses to a standard temperature. It is legitimate to run the motor significantly hotter in service, with consequently higher losses and lower efficiency, and motor designers may well design for a higher temperature. This is one of the issues that led to the decision to produce a different international standard for the measurement of motor efficiency.
- The distribution of known losses within a motor varies, but differences in the distribution would have minimal effect on the results obtained from the algorithm. A simple assumption is that the four known losses (stator copper losses, rotor copper losses, iron losses and windage plus friction losses) are each one quarter of the total of known losses. In reality, in small motors the stator copper loss tends to be a higher proportion, but on the other hand the winding temperature of efficient small motors tends to be lower. Thus assuming a higher proportion of stator copper loss plus a high winding temperature would tend to make the overall adjustment too great. Also, the main adjustment in the case of smaller motors is that for additional losses, and small differences in the assumed proportions of other losses have little effect.

These therefore give rise to equations 1 to 4 below.

Note that unlike in the standards, these equations are expressed in per unit terms, not in absolute units. For this reason, and because few of the values represented are the same as in the standards, the symbols used are generally different, and are:

\[ L_N = \text{Total estimated losses} \]
\[ L_{N,Cu} = \text{Adjusted copper losses (stator + rotor)} \]
\[ L_{N,FeW&F} = \text{Value of combined iron losses and windage & friction (IEC 61972)} \]
\[ L_O = \text{Total original losses per IEC 34-2} \]
\[ L_{O,Cu} = \text{Copper losses (stator + rotor) determined using IEC 34-2} \]
\[ L_{O,FeW&F} = \text{Combined iron losses and windage & friction (IEC 34-2)} \]
\[ P = \text{Motor rated output} \]
\[ S_N = \text{Additional losses assigned by IEC 61972 (draft)} \]
Efficiency Measurements

Converting Energy Efficiency Requirements to Account for Different Test Protocols

\( S_O \) = Additional losses assigned by IEC 34-2
\( \eta_N \) = New estimated value of efficiency
\( \eta_O \) = Efficiency determined using IEC 34-2
\( \rho_N \) = Resistivity of copper at maximum allowable temperature
\( \rho_O \) = Resistivity of copper at temperature assigned by IEC 34-2

\[
L_O = \frac{1}{\eta_O} - 1 \hspace{2cm} \text{Eqn 1}
\]

\[
S_O = \frac{0.005}{\eta_O} \hspace{2cm} \text{Eqn 2}
\]

\[
L_{O,Cu} = \frac{1}{2} \left( \frac{1}{\eta_O} - 1 - \frac{0.005}{\eta_O} \right) = \frac{1}{2} \left( \frac{0.995}{\eta_O} - 1 \right) \hspace{2cm} \text{Eqn 3}
\]

\[
L_{O,Fe&W} = \frac{1}{2} \left( \frac{0.995}{\eta_O} - 1 \right) \hspace{2cm} \text{Eqn 4}
\]

The losses are then adjusted such that:

\[
S_N = \frac{0.03 - 0.15 \left( \frac{\log P}{\log 200} \right)}{\eta_N} \hspace{2cm} \text{Eqn 5}
\]

\[
L_{N,Cu} = \frac{\rho_N}{2 \rho_O} \left( \frac{0.995}{\eta_O} - 1 \right) \left( \frac{\eta_O^2}{\eta_N^2} \right) \hspace{2cm} \text{Eqn 6}
\]

\[
L_{N,Fe&W} = L_{O,Fe&W} \hspace{2cm} \text{Eqn 7}
\]

\[
\eta_N = \frac{1}{1 + L_N} \hspace{2cm} \text{Eqn 8}
\]

In practice, when used in a spreadsheet, these equations are combined. However, the allocation of additional losses depends on the input to the motor (see Eqn 5), which itself depends on the final efficiency. The copper losses also change with efficiency. Therefore, iteration was used to determine the values of adjusted losses and efficiency.

2.3 Results

This process gave results that meet the principle of a motor tested in accordance with IEC 34-2 still meeting the new efficiency requirements, but with a margin that is unnecessarily large, indicating that a number of motors that would fail under IEC 34-2 would...
Easily pass if tested to the new test protocol. There are two factors contributing to this. One is that the adjustments made represent a coincidence of extreme conditions, which is very unlikely. The other is that one of the strategies to produce an efficient motor is to increase the copper area and thereby the copper losses, resulting in cooler winding temperatures. To account for these factors, an adjustment was made to the algorithm that had the effect that the increase in losses approximately halved. (In the event, a programming mistake resulted in the factor varying very slightly around one half, hence the use of the word approximately!) These results were then used to create efficiency levels equivalent to the European “eff 1” and “eff 2” curves for the new test protocol. Unfortunately the European requirements did not cover the whole range identified as being worthwhile to include in the programme for Australia (and, incidentally, in other countries’ programmes). Therefore the efficiency curves were extended to cover a greater range of outputs, and additional sets of values created for six-pole and eight-pole machines.

The resulting standards, AS/NZS 1359.5:2000 therefore had parallel sets of tables. Of each pair, one table gives minimum efficiency requirements for motors tested to IEC 60034-2 or equivalent. The other table gives minimum efficiency requirements for motors tested to AS/NZS 1359.2.3, IEC 61972 or equivalents.

Figure 2 shows that the effect of the process is to decrease the efficiency of high efficiency motors by between half and one percent, depending on output, and of lower efficiency motors by between one and two percent.

Figure 2: Effect of the translation algorithm
In time, the older test protocol will be dropped and will disappear as far as energy efficiency requirements are concerned. In the meantime, the method outlined above can be used by those changing to the new test protocol to adjust their efficiency requirements.

### 2.4 Applying the process to individual motors

The process was intended only for moving from the old test protocol to the new one, and for setting the new requirements. It was not intended for application to individual motors. However, given that it is expected to produce reasonably consistent results, there are probably only a few designs that pass a minimum efficiency requirement based on one test protocol but fail the equivalent efficiency requirement when tested to the other test protocol. The practical experience of members of the joint standards committee EL/46 developing the joint standard indicated that the requirements as formulated were compatible.

A further check was carried out during the drafting of this paper. One of the papers referred to (Williamson and Sambath) quotes results from testing five different 7.5 kW motors in accordance with various test protocols, including IEC 34-2 and IEC 61972. It is therefore possible to apply the conversion algorithm to the former test results, and compare them with the actual IEC 61972 measurements. The results are shown in Figure 3.

![Figure 3](image-url)  
**Figure 3** Comparison of the translation algorithm with practical results

Three of the results predicted are below the measured results, two of them only marginally. In the two cases where the measured efficiency is lower than predicted, the stray losses were towards the high end of the range to be expected. More importantly, those motors that meet the requirements for the European “eff 2” value also meet the
equivalent of AS/NZS 1359.5; those that are below the requirement for “eff 2” also fail to meet the equivalent requirement of AS/NZS 1359.5; while the motor that is within rounding up distance of meeting the "eff 2" requirement is also within rounding up distance of meeting the AS/NZS 1359.5 efficiency value.

This result indicates that the translation algorithm may be used to screen motors tested to the “wrong” standard for compliance with minimum efficiency requirements.

3 An alternative method

As had been pointed out above, the translation algorithm uses an iteration process that, while straightforward to perform, can be inconvenient if carrying out calculations on a complete database. A simpler method can be to use tables such as those in AS/NZS 1359.5 to set up a “look-up” table of the expected loss ratios for each output and speed of motor. The loss ratio (symbol $F$) for a particular size of motor is given by

$$F = \frac{(1 - \eta_A) \eta_B}{\eta_A (1 - \eta_B)}$$

Eqn 9

and for each motor, the predicted equivalent efficiency is obtained by adjusting its losses, thus giving

$$\eta_N = \frac{1}{1 + F \left( \frac{1 - \eta_o}{\eta_o} \right)}$$

Eqn 10

These conversions are for use on full load conditions. There is an assumption that around full load the power factor does not vary significantly. But if it is wished to use a similar conversion for other conditions, then either more motor data are required, or else additional assumptions will have to be made concerning the distribution of losses within the motor, the no-load current and the resulting power factor.

3.1 Application to programme monitoring

In New Zealand, the government agency that administers the energy efficiency regulations has the power to collect from motor suppliers annual data on numbers of motors sold and their efficiencies. These raw data may not be disclosed, but may be used to track improvements in average motor performance and the consequent reduction in energy consumption attributable to the motor MEPS programme.

As most of the motors supplied in the base years were tested to the old test protocol, most data collected needs to be manipulated to place all data on a common and long-term basis. This process is gradually decreasing as motor manufacturers are increasingly testing their motors to the IEC 61972 test protocol (Frost). For estimating actual in-service energy consumption it is the performance at 75% load that is considered
more relevant. The suppliers are therefore asked for this datum for each motor, and fortunately most of them do supply it.

3.2 Comparison with 60 Hz regions

The use of these conversion factors allows the energy efficiency programmes of different regions to be compared. This was done in a study for the Australian Government (Marker) that led to their proposal to increase their motor minimum efficiency requirements to the previous high efficiency level, which more nearly matched the minimum efficiencies required in North America. There is the consideration that the North American values are set for 60Hz motors as distinct from the 50Hz supply in Australia, but the conversion between 50Hz and 60Hz is another matter.

4 Conclusions

The conversion methods described allow motors to prove compliance with efficiency requirements regardless of which test protocol is used. It therefore represents a way of avoiding a potential barrier to trade, while also facilitating the availability of higher efficiency motors.

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User-Friendly High-Precision Electric Motor Testing System

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Abstract

In order to perform motor performance tests and training, a computer controlled high-precision full-automated electric motor testing facility was developed, described in this paper. The developed testing facility can be used to measure efficiency by direct or indirect methods of low-voltage electric motors up to 7.5 kW. The IEEE 112-B and the new IEC 61972 standard can be performed automatically using a user-friendly software and respecting instrumentation accuracy requirements and. This motor test bench can provide a suitable framework for testing the behavior of electric motors under different conditions, and it also provides a good introduction to automatic testing stations. The results of several tests are presented, including the comparison of the performance of low-power low-voltage copper squirrel-cage induction motors with aluminum squirrel-cage induction motors. The performance of induction motors driven directly by the grid or by a variable speed drive are also shown.

1 Introduction

The vast majority of the motors used in industry are squirrel-cage induction motors (IMs) due to their low cost, high reliability and fairly high efficiency. Additionally, in recent decades electronic controls have allowed induction motors to be used in high demanding applications requiring accurate torque/speed control.

The efficiency of a motor driven process depends upon several factors which may include motor efficiency, motor speed controls, power supply quality, system oversizing, distribution network, mechanical transmission, maintenance practices, load management and cycling and efficiency of the end-use device (e.g. fan, pump, etc.). In order to perform motor performance tests and training, a computer controlled high-precision full-automated electric motor testing facility was developed, described in this paper. The developed testing facility can be used to measure torque, speed, temperature, voltages, currents, power factor, reactive power and efficiency by direct and indirect methods of low-voltage electric motors up to 7.5 kW. The IEEE 112-B [IEEE, 2004] and the new IEC 61972 [IEC, 2002] standards can be performed automatically using an user-friendly software (developed in LabVIEW) and respecting the instrumentation accuracy requirements. The system allows a full control of line voltage and torque. This motor test bench can provide a suitable framework for testing the behavior of electric motors under different conditions, as well as it provides a good introduction to automatic testing stations. The results of several tests are presented, including the comparison of the performance of low-power low-voltage copper squirrel-cage (die-casting) IMs with aluminium squirrel-cage IMs. The comparative performance of IMs driven directly by the grid and by a variable speed drive (VSD) are also shown.
1.1 Motor Losses

There are four different kinds of losses occurring in a motor: electrical losses, magnetic losses, mechanical losses and stray losses. These losses can be reduced by increasing the quantity and quality of materials used, as well as by optimizing the motor design.

The electrical Joule losses are of the type $I^2R$, and consequently they increase rapidly with the motor load. These Joule losses can be mostly decreased by increasing the cross-section of the stator and rotor conductors, and by shortening the heads.

Magnetic losses occur in the steel laminations of the stator and of the rotor. They are due to hysteresis losses and eddy currents, and vary with the flux density and the frequency. They can be reduced by increasing the cross-section of the iron in the stator and rotor, by using thinner laminations, and by using improved magnetic materials.

Mechanical losses are due to friction in the bearings, ventilation and windage losses. They can be decreased using low friction bearings and improved fan design.

Stray losses are due to leakage flux, non-uniform current distribution, mechanical imperfections in the air gap, and irregularities in the air gap flux density. They can be reduced by optimal design and careful manufacturing.

Electric motors and, in particular, induction motors, are designed to operate with optimal performance, when fed by symmetrical 3-phase sinusoidal waveforms with the nominal voltage value. Deviations from these ideal conditions may cause significant deterioration of the motor efficiency and lifetime.

Voltage unbalance wastes energy: it leads to high current unbalance which, in turn, leads to high losses. A phase unbalance of just 2% can increase losses by 25%. Additionally, long operation under unbalanced voltage can damage or destroy a motor (that is why many designers include phase unbalance and phase failure protection in motor starters). Another negative consequence of unbalance is the reduction of the motor torque.

When the motor is running at or nearly full load, voltage fluctuations exceeding 10% can decrease motor efficiency, power factor and lifetime. Under ideal operating conditions, utilities supply pure sinusoidal waveforms (50 Hz frequency in Europe). However there are some loads, namely VSDs and other power electronic devices, arc furnaces, saturated magnetic cores (transformers, reactors), TVs and computers, that cause voltage distortion. The resulting distorted waveform contains a series of sine waves with frequencies that are multiples of the fundamental 50 Hz frequency, the so called harmonics. Harmonics increase the motor losses and noise, reduce torque, and cause torque pulsation and overheating. Vibration and heat can shorten the motor life, by damaging bearings and insulation.

Therefore, the efficiency measurement can only be accurate if the power supply quality is maintained within certain limits (defined by testing standards).
1.2 Motor Efficiency Testing

The efficiency of electric motors can be either measured directly or indirectly. Direct methods are generally more accurate, but its use has not been widespread around the world due to the need to minimize the costs associated with setting up the testing laboratories.

The measurement of the efficiency of electric motors, $\eta$, can be made directly using the equation:

$$\eta = \frac{T \cdot \omega}{P_{\text{elec}}}$$

where $T$ is the torque (N.m), $\omega$ the shaft speed (rad/s) and $P_{\text{elec}}$ the input electric power (W). It is therefore required to measure both the mechanical output power and the electrical input power. The electric input power can be measured with accuracy with a simple set up and with moderately priced equipment.

Whereas speed measurement is a relatively simple procedure requiring inexpensive equipment to achieve accurate results ($\pm 1$ rpm), torque measurement requires a more elaborate set up and much more expensive equipment to provide accurate results. The measurement of the torque normally requires coupling the motor to a dynamometer, which has the possibility of creating a variable load, fitted with an accurate torque transducer.

In North America the prevailing testing method is based on the direct measurement of the efficiency. The Institute of Electrical and Electronic Engineers (IEEE) Standard 112-B is the standard accepted both by the National Electrical Manufacturers Association (NEMA Standard MG-1) and by the US Department of Energy. In Canada the Canadian Standards Association (CSA) Standard C390, follows a very similar procedure to the IEEE 112-B Standard.

In order to avoid the complexity and associated expenses of torque measurement, the motor efficiency can also be indirectly measured through the following equation:

$$\eta = \frac{P_{\text{elec}} - P_{\text{losses}}}{P_{\text{elec}}}$$

where $P_{\text{elec}}$ is the input electric power (W) and $P_{\text{losses}}$ is the motor total power losses (W). This calculation requires the measurement of the motor losses. Most of the motor losses (Joule, magnetic and mechanical) can be measured with fairly good accuracy. However, the remaining losses (stray losses) cannot be accurately measured and some testing methods either assign them an arbitrary value (IEC 60034-2) or totally ignore those losses (JEC 2137).
2 Testing Facility

The developed motor testing facility can be used to determine the efficiency and losses according to both indirect testing and direct testing methods such as IEEE 112-B. In this case the calculations require the load test and the no-load test with different voltage levels to estimate the iron losses and windage and friction losses. The testing station has flexibility to determine automatically the efficiency according to any standard.

Basic equipment

The main modules of the system are (Figure 1): dynamometer (Magtrol, model HD-815-8NA), auto-transformer (Slidac, 230-295V, 20A), automated Voltage Regulator (Powerex), DC sources (HP, model E3631A), Pentium PC, data acquisition board (National Instruments, PCI-MIO 16E-4), power analyzer (Yokogawa, WT1030M), GPIB board and signal conditioning electronics.

Figure 1: Testing facility photograph and block diagram
Efficiency Measurements
User-Friendly High-Precision Electric Motor Testing System

Instrumentation accuracy

The minimum accuracy requirements of the instruments used to test the motor efficiency according to IEEE 112 and IEC 61972 standards are respected (see Table 1).

Table 1: Instrumentation accuracy of IEEE 112 standard [Almeida, 2001]

<table>
<thead>
<tr>
<th>Type of measurement</th>
<th>IEEE 112-B (Direct Method)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical</td>
<td>±0.2% of full scale</td>
</tr>
<tr>
<td>Frequency</td>
<td>±0.1% of full scale</td>
</tr>
<tr>
<td>Speed</td>
<td>±1 rpm</td>
</tr>
<tr>
<td>Torque</td>
<td>±0.2% of full scale</td>
</tr>
<tr>
<td>Electrical Resistance</td>
<td>±0.2% of full scale</td>
</tr>
<tr>
<td>Temperature</td>
<td>±1ºC</td>
</tr>
</tbody>
</table>

Power quality control

The automatic voltage regulator (AVR) guarantees that the supply voltage has voltages with an unbalance less than 1%.

Harmonic distortion can increase steeply the losses of electrical motors and therefore decrease the efficiency values of the motors being tested. The total harmonic distortion of the 3-phase supply is typically (and should be) under 1%. If a test facility has nearby factories with arc furnaces, large variable speed drives or other significant non-linear loads, power quality may be low. In this case, there may be a need to install harmonic filters to reduce harmonic distortion to under 1%.

Torque and Speed Measurement

The speed and torque measurement is provided by the dynamometer optical encoder and load cell, respectively. These signals are processed by the power analyzer which automatically calculates the mechanical power.

Load Torque Control

The computer data acquisition board analogue output is connected to a power operational amplifier which feeds the dynamometer winding. Therefore it is possible to use the computer to control the load torque from minimum residual to maximum torque given by the dynamometer. The maximum power which can be handled by the dynamometer is 7.5 kW.

Voltage control

The motorized autotransformer, connected after the AVR, allows the voltage amplitude variation from zero to 127% of line voltage (max.: 511 V, line-to-line). The incorporated motor is controlled by solid-state relays connected to the data acquisition card analogue output. Therefore it is possible to use the computer to control the amplitude of the voltage applied to the motor.
Temperature measurement

The operating temperatures are measured by thermocouples connected to the data acquisition card analogue inputs. The system has capacity to read simultaneously the temperature in 5 points. The distributed motor internal temperature is estimated from the stator winding electrical DC resistance measurement. In this process the line voltage must be disconnected and the motor stopped, and a DC voltage is applied to the windings. The resultant current, after its conversion to a voltage drop, is acquired with the data acquisition board.

Electric measurements

The voltage, current, power factor, active power, reactive power, apparent power, harmonics, totally harmonic distortion and frequency are measured directly by the three-phase power analyzer which has data communication with the PC. To increase the accuracy of electrical measurements of pulse width modulated (PWM) voltages, the power analyzer has an internal filter. The instantaneous voltages and currents values are measured by voltage and current sensors, connected to the acquisition board (these measurements are not needed for efficiency measurement purposes).

Software

The user-friendly developed software (LabVIEW environment) can generate automatically the efficiency and power factor curves as a function of the load, allowing an easy analysis of results and measurements. The software controls the equipment and data acquisition and performs mathematical operations and allows the visualization of results in tables and graphs.

3 Example 1: Application of the IEEE112-B Standard

In this section the results of the application of IEEE 112-B standard on two three-phase induction motors of 1.1 kW, 400 V, 4 pole, are presented. One of the tested motors has an aluminum squirrel-cage rotor and the other motor has a copper squirrel-cage rotor (die-casting), which is an emerging technology in the motor market. For both motors 2 tests were performed. One is the load test with different 6 load points, decreasing from approximately 150% to 25% of nominal torque. The other is the no-load test for iron losses as well as for friction and windage losses calculation, with voltages decreasing from 125% of the rated voltage to the point where voltage reduction starts to increase significantly the current.

After the load and no-load tests, the user can automatically visualize (and print) the results in table and graphical forms, including the efficiency, power factor and the losses.

In Figure 2 the losses distribution variation with the load is presented for the aluminum squirrel cage induction motor (4 pole, 1.1 kW) and for the copper squirrel cage induction motor (4 pole, 1.1 kW). In Figure 3 the efficiency and load factor variation with load can be seen for both motors.
The efficiency and power factor of copper squirrel-cage motor is significantly higher (at all load points) than of aluminum squirrel cage motor.

4 Example 2: Effect of VSDs on Motor System Efficiency

In this section the results of the application of IEEE 112-A standard (without loss segregation) on 3 three-phase induction motors of 3, 4 and 5.5 kW, 400 V, 4 pole, are presented. A 11 kVA VSD (type VSI-PWM with diode rectifier) was used. For the 3 motors a test with constant voltage and constant fundamental frequency (50 Hz) was performed with and without VSD. In this test the switching was set to 8 kHz. In Figure 4 the results for the efficiency and power factor for the motor system (VSD+IM) can be
seen. The introduction of the VSD leads to a small decrease of the motor system efficiency and to the improvement of the power factor, particularly at low loads, despite the use of a simple three-phase diode rectifier (which as no power factor correction ability).

A test with constant voltage and constant fundamental frequency (50 Hz) and different switching frequencies (4, 8, 12 and 16 kHz) was performed for the 3 kW motor system (VSD+IM). In Figure 5 the results for efficiency can be seen. For the nominal frequency, the increase in the switching frequency leads to an efficiency decrease.

Figure 4: Efficiency and Power Factor for 3 different IMs with and without VSD operating at constant voltage and constant fundamental frequency (50 Hz)

Figure 5: Influence of the switching frequency on the 3 kW motor system efficiency operating at constant voltage and constant fundamental frequency (50 Hz)
5 Conclusions

According to the IEEE 112 and IEC 61972 instrumentation accuracy requirements, the developed motor testing facility is able to perform automatically or manually a quick and accurate no-load to full-load analysis of low-voltage electric motors (up to 7.5 kW) including the measurement of efficiency (direct and indirect methods), power factor, speed, torque, external and internal operating temperatures, currents, voltages, active power and reactive power.

The IEEE 112-B standard automatic implementation is significantly faster than the manual/visual implementation, which requires the reading of the measure devices and introduction of values in a calculation sheet. The execution period is about 4 minutes, after the motor thermal stabilization, significantly lower than the 15 minutes typically required by manual implementation. Additionally, the possible human reading errors are eliminated. In the performed tests similar results were obtained with manual and automatic implementation of the tests. An important advantage is the user-friendly interface and the efficient graphical analysis of results generated by computer.

In the future this system is expected be upgraded to allow electric motor system regeneration testing, by incorporating a high inertia wheel and a shaft torque sensor. This is very important to test multiquadrant VSDs, e.g. used in the electric vehicles.

6 References

IEEE Std 112: Standard Test Procedure for Polyphase Induction Motors and Generators, 2004


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P. Van Roy; B. Renier; K. Hameyer; R. Belmans, Katholieke Universiteit Leuven, E.E. Dept., Div. ESAT/ELEN, Belgium, “A Practical Set-up for a Standard Test Procedure on Polyphase Induction Motors”

Abstract

This paper aims at demonstrating the need for a thorough scrutiny of induction motor efficiency measurement methods in current use. Moreover, it highlights the need for cognizance of many more factors that affect efficiency, such as unbalanced voltage supply conditions and power quality. After giving an overview of various different efficiency measurement techniques as embedded in standards the paper presents the results of efficiency tests performed in the laboratory according to a number of selected standard methods. It is shown that substantial discrepancies exist in results. The paper then discusses the effect of supply voltage unbalance on the performance of an induction machine and shows, on the basis of laboratory tests, that further discrepancies are introduced into the measured efficiency values.

1 Introduction

Against the backdrop of increasing (electrical) energy demand, diminishing resources accompanied by environmental concerns based on greenhouse considerations and increasing fossil fuel prices, efficiency has assumed paramount importance in recent years. More than 50% of the electricity consumption in the developed countries and approximately 65% of the electricity which is used in industry is consumed by electrical motors [de Almeida et al. 1997 / De Keulenaer et al. 2004 / Collard et al. 2004]. Therefore, the efficiency of motor driven systems is of major importance, especially in the case of induction motors which constitute the bulk users of energy in industrial societies. Evidently, even a modest increase in motor efficiency would yield considerable benefits in both environmental and economical terms. Governments, which have a responsibility to inform and to regulate, have been increasingly proactive in matters pertaining to device efficiency. There are numerous examples of national and international agreements, incentives and initiatives worldwide. For Europe, this is reflected in different ongoing programmes. For instance, ‘The European Motor Challenge Programme’ and the most recent classifications of industrial a.c. motors on the basis of their certified efficiency, e.g. EFF1, EFF2, EFF3 labels of the CEMEP (the European Committee of Manufacturers of Electrical Machines and Power Electronics) voluntary agreement [De Keulenaer et al. 2004].

Evidently these efficiency classifications presuppose that efficiency measurement methods are well established beyond reproach and agreed upon in national and international standards. A closer examination of standards, however, reveals that there are major discrepancies between the methods proposed by different standards. This has
serious consequences both in terms of issuing certificates and credibility of the declared efficiency values for decision making when purchasing motors. The prescribed methods become all the more wanting for non-ideal operating conditions of a real application as opposed to the ideal test conditions of the standard methods. For instance, standards are conspicuously silent on matters pertaining to unbalanced supply or poor power quality. Also, the practice of certifying efficiency on the basis of a single efficiency value must be questioned.

This paper gives an overview of the most prevalent standards on efficiency measurement and of the different definitions of voltage unbalance. The effect of voltage unbalance on induction motors and their performance is addressed. Some standards concerning voltage unbalance and their consequences on induction machine performance are discussed. Throughout the paper, the discussion is backed up by results of efficiency measurements conducted in the laboratories of the Electrical Engineering Department at the KULeuven.

2 Efficiency Measurement

Motor efficiency is measured on the basis of standards and normally eludes to 'energy efficiency'. Disturbingly, different efficiency values are obtained for the same machine from the same test depending on which standard is taken as the basis of efficiency determination. Obviously, there are possible consequences of such discrepancies in measured efficiency values when they are used for the purpose of optimising the energy efficiency of motor driven systems.

2.1 Energy Efficiency of Induction Machines

Theoretically, the definition of energy efficiency is very simple:

\[
\eta = \frac{P_{out}}{P_{in}} = 1 - \frac{P_{loss}}{P_{in}}
\]  

(1)

In practice however, a series of different standards, based on (1), lead to differences in efficiency values of several percent [Slaets et al. 2000 / Renier et al. 1999]. This theoretical definition (1) provides the licence for dividing the efficiency measurement methods into two categories: direct and indirect methods. For induction machines, this means that for the direct method the output power has to be determined. This necessitates a torque and a speed measurement. But, efficiency values obtained by this method also depend on ambient and motor temperature, which is not desirable for a transparent efficiency comparison. The second method allows the correction for these temperature values to a specified ambient and reference motor temperature. This is realised by correcting the individual loss components. Yet, the main difference between the standards emerges from the way in which the so-called stray load losses - as a part of the overall losses - are treated [Slaets et al. 2000 / Renier et al. 1999].
2.2 Losses in Induction Machines

The losses in a three phase squirrel cage induction motor can be divided into five categories. These individual loss components and the methods for determining their values are now discussed briefly. An extensive discussion of these loss components can be found in literature [Nürnberg & Hanitsch 1987 / Renier et al. 1999].

The first four loss components are stator and rotor ohmic ($P_{stator,RI}$ & $P_{rotor,RI}$) losses, core losses ($P_{Fe}$) and the friction and windage losses ($P_{fr,w}$). The core and friction and windage losses are obtained from a no-load test. The ohmic losses are determined based on stator resistance, slip and input power measurements. Most standards also prescribe how to correct the ohmic losses for a specified ambient temperature and a reference motor temperature [Standards: IEEE and IEC].

The fifth loss component, the additional load losses, also known as stray load losses, is the most ambiguous of all the loss components, although it is simply defined as:

$$P_{addit} = (P_{in} - P_{out}) - (P_{Fe} + P_{stator} + P_{rotor} + P_{fr,w})$$ (2)

The stray load losses are caused by time and space harmonics and by the leakage flux near the winding ends. In the past, several methods have been proposed to measure these additional load losses, including the reverse rotation test at slip 2 or half frequency tests at slip -1 and 3. However, these methods have proved neither reliable nor practical for the determination of efficiency of induction machines.

2.3 Standards for Efficiency Measurement

World-wide, there exist several standards for determining the efficiency of induction motors. Of these the three most important are:

- IEEE Standard 112-1996
- IEC 60034-2 Ed.3
- JEC.

2.3.1 IEEE Standard 112

The IEEE 112 standard defines several methods how best to test electric motors. Efficiency determination is only part of this standard, although it is an important one. Some of the key (there is a total of 10) test methods for efficiency are:

- Method A: simple input-output
- Method B: input-output with loss segregation (or separation)
- Method C: back to back machine test with separation of losses
- Method F: equivalent circuit (model) calculation.

The other methods, E, E1, F1, C/F, E/F and E1/F1 are variations of these. Method A, which is only recommended for small machines, is a direct method. Method B is in fact an indirect method, but it uses a direct method to obtain a value for the additional
losses. The measuring error is reduced by linearising the additional losses and correcting them for zero additional losses at no load. The correlation coefficient of the linear regression should be higher than 0.9. Method B is the recommended and the most popular method for testing of induction machines up to 180 kW.

2.3.2 IEC Standard 60034

Just as with the IEEE Standard 112, the IEC 60034 Standard defines how best to test electrical motors. The second part of this standard, IEC60034-2, describes how to determine the losses and efficiency from tests (excluding machines for traction purposes). This standard also provides different techniques to determine the different loss components, e.g. a breaking test with torque measurement, a back to back test, etc. Historically, due to difficulties of torque measurement, the current IEC standard for determining motor efficiency (IEC 60034.2 Ed. 3 (1972)) assumes a standard value for the additional load losses at rated load of 0.5% of the input power. Note that IEEE112-E1 sets the additional losses as 1.8% of the rated output power for motors between 0.75 kW and 90 kW. An intermediate proposed standard, the IEC 61972, gave two possibilities. The first was a method similar to IEEE112-B, the second attributed a fixed amount to every machine of the same rated output power. However, the latest proposed draft for the revised IEC 60034-2 (4th edition) recommends that for three phase induction machines between 1 kW and 150 kW the additional losses should be determined by the direct method as in the IEEE112-B standard. The approval of this proposal by the committee would be a significant improvement as already anticipated in literature [Slaets et al. 2000 / Renier et al. 1999 / Van Roy 2003] and supported by the experimental evidence below.

2.3.3 JEC Standard on induction motor efficiency

As far as it could be ascertained by the authors, the Japanese JEC Standard 37 still completely neglects the additional load losses.

2.4 Measurements

To illustrate the discrepancies that can exist in efficiency determination using different standards, a modern small 1.1 kW standard three phase squirrel cage induction motor was tested in laboratory, using the test setup shown in Fig.1.

In the setup, the brake is a Vibrometer water-cooled Eddy Current - Powder Brake combination. The torque transducer (type T30FN of HBM) is used in combination with a KMN913.C measurement amplifier of HBM. This combination allows the output power to be determined with an accuracy of better than 0.5%. This brake-torque transducer combination can be used to test machines up to 3 kW at 3000 rpm. The input power, input voltages and currents are directly measured using a Voltech PM3000A Power Analyser. The input power measurement accuracy is 0.4%. A LabVIEW® based data acquisition system was used.
Before the start of measurements, ambient temperature and the winding temperature are measured. Then, the motor is warmed up under rated load until thermal equilibrium is reached. This is checked by measuring the winding temperature again. Next, the load test is performed. Starting at 125% of rated load, about 20 load points are set and measured. And finally, the standard no-load test, with disconnected brake, is performed. During this test, the induction machine is run as a motor with different values of the stator voltage.

Based on these measurements, a spreadsheet automatically generates efficiency values in four different ways. The first is derived from the direct method as described by (1). The three other efficiency curves are those obtained according to IEEE standard 112 Method B, IEC 60034-2 standard (with the factor of 0.5% for the additional losses)
and the JEC respectively. Fig.2. shows the efficiency according to these four methods as a function of normalised torque.

The difference between the measured efficiency and the catalogue value is 3.5% for the IEEE112B based efficiency and 1.1% for the IEC (0.5%) one at full load. The difference between the IEEE and the IEC efficiency is 2.44%. The calculated stray load losses are 2.09% of the rated output power. This clearly illustrates that the factor of 0.5% for stray losses is a serious underestimation and that the factor of 1.8% of IEEE Standard 112 Method E1 is more realistic. These conclusions are in agreement with findings based on measurements of 18 motors of 11 kW, 55 kW and 75 kW rating [Slaets et al. 2000 / Renier et al. 1999 / Van Roy 2003].

2.5 Discussion

The above shows that measured efficiency values of induction motors are not unambiguous: they just depend on the standard used in determining the efficiency! This underlines the expectation that the only correct way to determine the efficiency of an induction motor is by the direct determination of the additional losses: all other methods overestimate the efficiency. This could pose problems when issuing certificates. For instance, the voluntary agreement of CEMEP concerning the efficiency labels issues an EFF3 label for 4 pole 1.1 kW motors with an efficiency below 76.2%, an EFF2 label if the efficiency is above or equal to 76.2% and an EFF1 label if the efficiency is above 83.8%. For the measured motor, this means that according to IEEE standard 112-B, the motor does not qualify for an EFF2 label, whereas according to the IEC standard (estimating the stray load losses as 0.5% of rated input power) the motor gets the EFF2 label comfortably. This has serious ramifications in the context of improving the efficiency of motor driven systems.

There are further aspects that influence efficiency determination in motor driven systems. Firstly, there is the problem of issuing efficiency certificates on the basis of a single load condition. Since the shape of the efficiency curves (see Fig.2.) can differ from manufacturer to manufacturer and from motor type to motor type, as was demonstrated in [Slaets et al. 2000 / Renier et al. 1999], the use of efficiency labels can be misleading from the point of view of the motor purchaser and unfair from the motor manufacturers’ point of view. It seems not unreasonable that manufacturers ought to be required to declare partial load efficiency values also, at least for 75% and 50% of the rated load. It is not clear how or whether this problem should be solved. But possible solutions would be the revision of the efficiency labels or the introduction of an extra penalising factor reflecting the shape of the efficiency curve.

A second issue concerns the effect of power supply quality on efficiency. IEC standard 60034-1 for efficiency measurements allows for a certain total harmonic distortion factor and a certain maximum unbalance for the supply voltage. However, these conditions do not always correspond to real life situations. It is shown that unbalanced supply voltages considerably affect induction motor efficiency [Pillay et al. 2002 / Wang 2001 / Lee 1999]. This issue is addressed in more detail in the next section.
3 Voltage unbalance and induction machines

In a three-phase system, voltage unbalance is the phenomenon in which the rms values of the voltages or the phase angles between consecutive phases are not equal. This can occur due to incomplete transposition of power lines, uneven distribution of single-phase loads, open delta transformer connections, blown fuses on three phase capacitor banks and so on. Voltage unbalance can negatively influence the efficiency of three phase induction motors and even shorten their service life.

3.1 Definitions and Standards

3.1.1 Definitions

There are several definitions of voltage unbalance in standards and the literature [Pillay et al. 2002]:

- NEMA uses the line voltage unbalance rate (LVUR) given by
  \[ \%LVUR = \frac{\text{Max Voltage Deviation from Avg Line Voltage}}{\text{Avg Line Voltage}} \times 100 \]  
  \[ \text{(3)} \]

- IEEE defines voltage unbalance as the phase voltage unbalance rate (PVUR) as
  \[ \%PVUR = \frac{\text{Max Voltage Deviation from Avg Phase Voltage}}{\text{Avg Phase Voltage}} \times 100 \]  
  \[ \text{(4)} \]

- IEC defines the voltage unbalance factor (VUF) expressed as
  \[ \%VUF = \frac{V_2}{V_1} \times 100 \]  
  \[ \text{(5)} \]

In equation (5) \( V_1 \) and \( V_2 \) are the positive and negative sequence voltages respectively, which can be obtained by symmetrical component transformation. This is the only definition which includes information of both magnitudes and phase angles. \( V_1 \) and \( V_2 \) are phasor quantities although often only the magnitude of VUF is considered. To avoid the use of complex algebra, it is proposed [Pillay et al. 2002] to use equation (6) which provides a good approximation to the ‘true’ IEC definition of unbalance:

\[ \text{\% voltage unbalance} = \frac{82 \cdot \sqrt{V_{\text{abe}}^2 + V_{\text{bce}}^2 + V_{\text{cae}}^2}}{\text{Avg Line Voltage}} \times 100 \]  
\[ \text{(6)} \]

with \( V_{\text{abe}} \) being equal to the difference between the line voltage \( V_{\text{ab}} \) and the average line voltage, etc.

Not surprisingly, the above three definitions provide different values to characterise the unbalance. For instance, one value of VUF can correspond to different unbalanced situations. In the case of PVUR, which does not incorporate any phase angle information, can give 0% unbalance even though the phase angles may be greatly unbalanced as long as the magnitudes are the same.
3.1.2 Standards

Several IEEE and IEC standards concerning “Power Quality” in fact discuss “normal operating conditions” [Bollen 2000]. Concerning voltage unbalance, the European voltage characteristics standard states the following [EN50160]:

“Under normal operating conditions, during each period of one week, 95% of the 10 minute mean rms values of the negative phase sequence component of the supply shall be within the range 0 to 2 % of the positive phase sequence component. In some areas with partly single phase or two phase connected customers’ installations, unbalances up to about 3 % at three phase supply terminals occur.”

The ANSI standard limits it to 3 % at the electricity meter under no load conditions [Lee 1999]. Such standards do not imply compulsory compliance; the supply companies strive to deliver a product according to this standard, but they can not or do not always guarantee it. In practice, the voltage unbalance can exceed that 2 or 3 % level. Moreover, voltage unbalance at the motor terminals can also be caused within the infrastructure of companies themselves. Industrial and commercial facilities may have well balanced incoming supply voltages, but unbalance can develop within the premises due to non-uniformly distributed single-phase loads, unbalanced or overloaded equipment, high impedance connections (e.g., bad or loose contacts), badly repaired motors, etc. Sometimes, unbalance and/or over voltages are also caused by improper power factor correction. Note also that the standards do not include any reference to phase angle information.

Voltage unbalance can have a detrimental effect on three-phase induction motors. This is considered in 3.2. To protect induction machines, the NEMA Standard MG 1-1993: Motors and Generators and the IEC 60034-26 prescribe that the machines must be derated. For instance, NEMA directs that an unbalance of 3 % requires a 12 % larger motor. It should be noted that these two standards use different voltage unbalance definitions.

3.1.3 Effect of Voltage Unbalance on Induction Motors

The adverse effects of unbalanced voltages on induction motors have been studied at least since the 1950s [Lee 1999]. It is common to study the behavior of the positive and negative sequence components of the unbalanced supply voltage to understand the effect of unbalance on the motor. The positive sequence voltage produces a positive torque, whereas the negative sequence voltage gives rise to an air gap flux rotating against the forward rotating field, thus generating a detrimental reversing torque. So in fact, the motor behaves as consisting of two separate motors, one running at slip s with terminal voltage $V_p$ per phase and the other running with a slip of $(2-s)$ and a terminal voltage of $V_n$. The result is that the net torque and speed are reduced with possible torque pulsations and noise. At normal operating speeds, the unbalanced voltages cause the line currents to be unbalanced in the order of 6 to 10 times the voltage unbalance [IEC 60034-26]. With reduced overall torque the motor will take longer to speed up, changing its thermal behaviour detrimentally. Further, if full load is still de-
manded, the high slip, and hence the low negative sequence impedance \( R'/(2-s) \),
give rise to large negative sequence currents, generating more heat. The reduction of
peak torque compromises the ability of the motor to ride through dips and sags. Prematu-
re failure can be prevented to some extent by derating the machine according to the
standards, allowing the machine to operate within its thermal limitations.

### 3.1.4 Measurements

Further tests were conducted to study the way that supply unbalance affects the effi-
ciency of three-phase induction motors. The test setup was the same as in Section 2.4
and Figure 1. Also, the same induction motor was used as for the standard efficiency
measurements of Section 2.4.

#### Setup

To create an unbalanced voltage supply a transformer \((230V : 24V)\) was placed in each
line. The transformers were fed with an adjustable voltage in phase with each corre-
sponding phase voltage of the power supply. Three different unbalance situations were
created: one with 2% VUF and the others with different supply voltage settings with a
VUF of 3%. Table 1 gives an overview of these different conditions of voltage supply.

<table>
<thead>
<tr>
<th>case</th>
<th>Va [V]</th>
<th>Vb [V]</th>
<th>Vc [V]</th>
<th>LVUR [%]</th>
<th>PVUR [%]</th>
<th>VUF [%]</th>
<th>VUFA [%]</th>
<th>V1 [V]</th>
<th>V2 [V]</th>
</tr>
</thead>
<tbody>
<tr>
<td>3%A</td>
<td>230</td>
<td>230</td>
<td>210</td>
<td>2.96</td>
<td>5.97</td>
<td>2.99</td>
<td>2.98</td>
<td>223.3∠0</td>
<td>6.67∠-60</td>
</tr>
<tr>
<td>3%B</td>
<td>234</td>
<td>234</td>
<td>213</td>
<td>3.06</td>
<td>6.17</td>
<td>3.09</td>
<td>3.07</td>
<td>227∠0</td>
<td>7∠-60</td>
</tr>
<tr>
<td>1%</td>
<td>234</td>
<td>230</td>
<td>218</td>
<td>2.04</td>
<td>4.11</td>
<td>2.11</td>
<td>2.12</td>
<td>227.3∠0</td>
<td>4.81∠46.4</td>
</tr>
</tbody>
</table>

The test results are presented in Figure 3. Efficiency is calculated according to the
standard IEEE112 Method B. Due to equipment limitations the measurements with a
VUF of 1% were made up to 95% of nominal load only. Although only three unbalanced
situations were considered, some important conclusions can be drawn. Firstly, unbal-
anced supply conditions that are well within the margins of the standards can adversely
influence the efficiency. In this experiment there is an efficiency decrease of about 1%
for nominal load conditions. Note that the IEC definition of voltage unbalance (VUF) is
used. Secondly, the change in efficiency is not solely proportional to the VUF. This is
illustrated by the fact that the efficiency for the VUF of 2% is worse than the efficiency
for the 3% VUF cases. Thirdly, different unbalanced supply cases with the same VUF
can result in different efficiency values.
Future Work

The crossing over of the two ‘3%VUF’ efficiency curves in Figure 3 begs for an explanation which could be found in the difference of positive and negative sequence voltages. A possible explanation for the worse efficiency of the 2% unbalance case may be found in the deviation of the phase angles of the negative and homopolar sequence voltages. It is not inconceivable that different motor designs have different sensitivity to unbalance and thus it is possible that an EFF1 motor is less efficient than some EFF2 motors under the same unbalanced conditions. To provide a scientifically based explanation for these effects, further investigation is required using additional measurements on motors of different rating by different manufacturers (thus of different designs) supported by simulations based on discrete circuit modelling and/or Finite Element Analysis.

4 Conclusion

The observations presented in this paper expose vagaries of efficiency measurement methods prescribed by reputable standards. It seems that there is need for a more unified and rigorous approach to efficiency determination in motor driven systems. There is a further need for the cognizance of operating realities such as power quality (e.g. unbalanced supply conditions) in the determination of induction motor efficiency, which standards presently ignore.
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Policies and International Issues I
Energy Efficient Motor Driven Systems

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Abstract

This paper makes a new synthesis of the potential for high-efficiency motor driven systems in Europe. Based on the 5 SAVE studies addressing motor systems, it presents the benefits and the main market barriers, and explains why adequate regulation will be necessary to overcome those barriers.

According to the study, motor driven systems account for approximately 65% of all electricity consumed by EU industry. It concludes that implementing high-efficiency motor driven systems can save Europe over 200 TWh of electricity and 100 million tonne of greenhouse gas emissions annually. Some additional benefits were quantified as well:

- A € 10 billion reduction per year in operating costs for industry
- A € 6 billion annual savings for Europe in reduced environmental costs
- A 45 GW reduction in the need for new power plant capacity over the next 20 years
- A 6% reduction in Europe’s energy imports

The SAVE studies also agreed on the main market barriers presently limiting the adoption of high-efficiency motor systems. Most relate to either the higher purchase cost or to lack of expertise on the part of both vendors and purchasers. Only adequate regulation, combined with information campaigns, is likely to overcome those barriers. Mandatory auditing schemes, financial support for training and certification and financial incentives for energy saving projects are some of the measures suggested by the paper.

1 Introduction

Motor driven systems account for approximately 65% of the electricity consumed by EU industry. New products and techniques hold great promises for large electricity savings. Implementing high efficiency motor driven systems, or improving existing ones, could save Europe over 200 TWh of electricity per year. This would significantly reduce the need for new power plants and hence free up capital and resources. It would also reduce the production of greenhouse gases and push down the total environmental cost of electricity generation. High efficiency motor systems can reduce maintenance costs and improve operations in industry.

Nevertheless, adoption of high efficiency motor driven systems has been limited by a number of factors, including their higher purchase cost and the lack of knowledge in the market place about their energy savings potential. Also prejudices regarding the reliability of such systems have negatively influenced their introduction. Few people know that, in the majority of cases, investments in high efficiency motor systems have a short pay-back time. Effective regulation combined with information campaigns should help
to stimulate change and bring significant benefits to the European economy and environment. This would increase the competitiveness of European manufacturing industry and improve its position with respect to those regions that have already taken significant steps towards improving energy efficiency.

2 Benefits of Implementing Energy Efficient Motor Systems

The best kWh is the one saved. Indeed, saving energy is beneficial for many reasons. Less fuel needs to be burned and fewer power plants need to be built. This saves money as well as saving the environment. Motor driven systems consume about 65% of industrial electricity in the European Union. The SAVE studies supported by the European Commission identified that, where modern high efficiency equipment was properly selected and installed, large energy savings were possible. Making energy savings a high priority is likely to yield significant financial benefits.

2.1 Electricity savings potential

2.1.1 Economic savings potential

Total electricity consumption in the EU-15 in 2000 was 2 574 TWh, of which 951 TWh was used in industry. Of this, 614 TWh, or 65%, was consumed by motor driven systems. The SAVE studies calculated the economical savings potential of those industrial motor driven systems to be 181 TWh, or 29%. This means a savings potential of more than 7% of the overall electricity consumption in the EU.

The above figure is the 'economic energy savings potential'. This is the savings potential of measures with a reasonable pay-back time, typically between 2 and 3 years. Its calculation is based on current electricity prices and can therefore vary with time. The 'technical energy savings potential' is the energy that would be saved by implementing all existing technical measures, without concern for economic efficiency. The technical savings potential is, of course, higher than the economic.

2.1.2 The motor and its application

Industrial facilities use very large numbers of motor driven systems, hereafter called motor systems. A motor system consists of the electric drive itself, sometimes a variable speed drive (VSD) and the driven load. Compressed air, pumping or ventilation systems represent about 60% of the motor loads. Other important uses include materials processing (mills, mixers, centrifugal machines, etc) and materials handling applications (conveyors, hoists, elevators, etc).

The efficiency of a motor system depends on several factors, including:

- motor efficiency
- motor speed control
- proper sizing
- power supply quality
- distribution losses
- mechanical transmission
- maintenance practices
- end-use mechanical efficiency (pump, fan, compressor, etc).

Figure 1 illustrates the synergistic effects of the combination of different energy efficient technologies to reduce the electricity consumption of a pumping system by more than half.

Table 1 specifies the energy savings potential in industry in the EU of using high efficiency motors (HEM), installing variable speed drives (VSD) and optimising the application part of the drive system.

Figure 1: a) Conventional pumping system (total efficiency = 31%)
   b) Energy-efficient VSD pumping system (total efficiency = 72%)

Table 1: Overview of energy savings potential for motor systems in the EU

<table>
<thead>
<tr>
<th></th>
<th>Savings potential (billion kWh/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>EU-15</td>
</tr>
<tr>
<td>High efficiency motors</td>
<td>24</td>
</tr>
<tr>
<td>Variable speed drives</td>
<td>45</td>
</tr>
<tr>
<td>Driven system</td>
<td>112</td>
</tr>
<tr>
<td>Total electricity savings</td>
<td>181</td>
</tr>
</tbody>
</table>
2.2 Environmental benefits

2.2.1 Kyoto target

One of the major current environmental concerns are the 'greenhouse gas' emissions (CO$_2$, N$_2$O, etc) amongst others created by the use of fossil fuels. After signing the Kyoto protocol in 1997, the EU committed itself to reduce its overall greenhouse gas emissions over the period 2008 to 2012 by 8% compared to 1990 levels, i.e. a reduction of 336 million tonne CO$_2$ equivalent (CO$_2$eq). This cannot be achieved without serious efforts in all areas of the economy, including the generation and use of electrical energy. There are four ways of reducing CO$_2$ emissions from electricity:

- increase the use of renewable energy sources
- increase the use of nuclear power
- through cogeneration and increased power plant efficiency (e.g., by using other fuels)
- energy saving.

Of these, energy saving currently offers the biggest potential at the lowest cost.

Power generation in the EU results in an average CO$_2$ emission of 0.435 kg CO$_2$/kWh (EU-15, 1999). This means that the savings potential on industrial motor systems of 181 TWh (EU-15) corresponds to the saving of 79 million tonne CO$_2$, or 24% of the Kyoto target. This is the annual amount of CO$_2$ that would be saved by 360 million solar roofs, or that an average European forest of 355 500 km$^2$ transforms into oxygen, i.e., an area larger than Finland.

Table 2 shows the emission reduction potential as a proportion of the 'Kyoto gap', i.e., the difference between expected emissions and 2010 Kyoto target emissions:

- France: Emission reduction potential is small because of the high proportion of nuclear generation. However, improving efficiency of motor driven systems would release emission-free electricity for sale to other countries.
- Germany: Emission reduction is larger than the Kyoto gap, making an additional 10 million tonne CO$_2$ emissions available for trade.
- Italy: Emission reduction represents 26% of the Kyoto gap.
- UK: Current policy measures are expected to meet the Kyoto targets. Emission reduction due to high efficiency motor driven systems would give the UK 12 million tonne of tradable credits.

Table 2: Overview of the CO$_2$ reduction potential related to efficient motor systems

<table>
<thead>
<tr>
<th>Reduction potential (million tonne CO$_2$ per year)</th>
<th>EU-15</th>
<th>EU-25</th>
<th>France</th>
<th>Germany</th>
<th>Italy</th>
<th>UK</th>
</tr>
</thead>
<tbody>
<tr>
<td>% of Kyoto gap</td>
<td>24%</td>
<td>n/a</td>
<td>6%</td>
<td>175%</td>
<td>26%</td>
<td>n/a</td>
</tr>
</tbody>
</table>
2.2.2 Non-greenhouse gas emissions

The burning of fossil fuels for electricity generation produces various types of emissions. Apart from CO₂, the main offenders are SO₂ and NOₓ, contributing to the acidification of the environment. These pollutants have long range trans-border effects and have therefore become a major concern for most European countries. The European Union participates in the UN sponsored Geneva Convention on Long Range Trans-border Air Pollutants being the international body attempting to reduce this type of pollution.

Additionally, emissions also contain heavy metals (nickel, zinc, chrome, copper, mercury etc) and dust. Although they can be substantially reduced by using the latest flue gas cleaning techniques, a small amount will always escape into the environment. Burning fossil fuels also produces fly ashes and solid ashes.

The 202 TWh that can be saved by optimising industrial motor systems means a reduction of 7% in the overall European electricity production, so it will lead to an equivalent reduction of all the emissions mentioned above.

2.2.3 Cost of burning fossil fuel

A European Commission research project calculated the cost of the environmental impact of power generation in Europe. These "fuel cycle externalities" are the costs imposed on society and the environment not included in the market price, for example the effects of air pollution, influences on public health, occupational diseases and accidents.

There is a wide range in estimates for external costs reflecting, for example, political preferences, or the use of different technologies for power generation.

So the environmental cost of an average European kWh is calculated at around 3 c€. This needs to be added to the typical industrial market price of 5 c€/kWh. Current eco-taxation schemes in the EU member states do not internalise the full external costs of electricity generation.

Saving 202 TWh/year in electricity also means saving € 6 billion of environmental costs for society.

2.2.4 Energy efficiency and energy sector investments

Improving the industrial motor systems in Europe (EU-25) could result in an annual saving of 202 billion kWh of energy consumption. This would eliminate the need for adding 45 GW of power generating capacity to the European electricity system. This is equivalent to:

- 45 nuclear power units (1 000 MW)
- 130 fossil fuel power units (350 MW)
The 202 TWh is equivalent to about five times the electricity production of all wind power units in Europe (EU-25) in 2003 (5 x 40 TWh).

The EU needs to add 320 GW of new base load capacity in the next 30 years to cope with increasing electricity demand. This expansion will cost Europe between €200 and €300 billion and High efficiency motor systems would reduce this expansion need by more than 10% and would save Europe around €25 billion.

2.3 Micro economical benefits

The pay-back periods for most investments in energy efficient motor systems are relatively short, ranging from 3 months to 3 years.

The non-energy benefits of higher efficiency systems are better process control, reduced disruption and improved product quality. Sometimes reliability is improved, but not always (a variable speed drive may be less reliable than a direct on-line system, although the reliability has improved dramatically since the introduction of IGBT components). Overall cost savings related to these benefits can be in the same order of magnitude as the energy cost saving itself. So companies or organisations that invest in energy saving on motor systems also improve profit in an indirect way.

2.4 Macro economical benefits

2.4.1 Increased competitiveness

Using energy as efficiently as possible is a crucial requirement to maintain the competitiveness of the European economy. Since motor systems account for 65% of all industrial electricity use, they are the most important area of attention for cutting energy costs.

2.4.2 Reduced dependency of fossil fuels

Saving 202 TWh a year (EU-25) also improves Europe’s security of supply and reduces dependency on fossil fuel imports. It represents 42.5 million tonne oil equivalent annually, reducing imports of primary fuel by 6%15. Therefore, saving energy on motor drives would allow more time to develop alternatives for fossil fuels. With just this argument in mind, it would even be defensible to look beyond the current economic savings potential of motor, and to encourage technology that can make them as energy efficient as possible. In other words, in the long-run, a large portion of today’s technical savings potential could become tomorrow’s economic savings potential.

3 Market barriers

If the savings potential of energy efficient motor systems is as high as described in Section 2, why does it receive so little attention? What are the restraints preventing
implementation of energy efficient drive systems? If those restraints are removed, which mechanisms can still block the actual implementation of more efficient systems?

Studies show that a whole spectrum of causes exists. Some of them are specific to certain industrial sectors or certain categories of motor systems (e.g., pumps, compressors, fans). Nevertheless, some general observations stand out. The following nine types of market barriers, grouped into categories according to importance, describe the largest part of the problem:

3.1 Major barriers
(1) Pay-back time is too long due to low electricity prices
(2) Reluctance to change a working process
(3) Split budgets

3.2 Medium barriers
(1) Not all parties in the supply chain are motivated
(2) Lack of correct definitions of motor system efficiency
(3) Oversizing due to lack of knowledge of mechanical characteristics of load
(4) Lack of management time

3.3 Moderate barriers
(1) Shortage of capital
(2) Other functional specifications conflict with energy efficiency.

4 Solutions

Overcoming market barriers

How can the barriers be overcome so that the European market for motor systems can be transformed? The conventional wisdom is that a good mix of actions, spread intelligently over time, is the best way. Co-ordinating all activities under a single central program will enhance the clarity of the benefits for the target audience and help to achieve the goals.

One proven tactic for changing a market is the three-tiered approach of the carrot, the stick, and the tambourine. The carrot represents the incentives, the stick regulation, and the tambourine stands for education. All three pillars are equally important.
The most important actions to overcome the barriers and achieve success can be summarised as follows:

1. **Regulation** - for example creating efficiency classes, licensing of motor systems as a part of the Integrated Pollution Prevention and Control (IPPC) operating licence of industrial installations, and mandatory audits.

2. **Information and education** - providing publications and seminars, tackling issues from the point of view of the target audience.

3. **Shop floor assistance** - decision-support tools (electronic databases, energy savings calculators, education of personnel on the job and, above all, energy audits).

4. **Financial support** - kick-start promotional rebates, support of distributors, enhanced capital allowances, special leasing contracts and the trading of emissions credits. In each case, incentives should be of adequate value in order to be successful.

5. **Working with suppliers** - the ideal partners for distributing information, but a perceived loss of independence should be avoided.

6. **Environmental standards** - accreditations like ISO 14001 as a framework to promote efficiency.

7. **Supporting R&D of manufacturers** - supporting R&D directly or indirectly results in designing more energy efficient products.

8. **Procurement & life cycle costing** - a proven technique to increase business and environmental performance at the same time.

9. **Integrated approach** - none of the above solutions will work in isolation but, combined, provide a powerful tool for change.

### 5 Ongoing programs

A number of programs for promoting enhanced motor system efficiency has been initiated in the European Union and the United States. They each concentrate on certain types of activities.

A short description of each of these programs is given below, followed by the most important lessons that could be derived from them.

#### 5.1 Regulation

1. The European Motor Challenge Programme - a voluntary programme instituted by the European Commission to improve the efficiency of motor driven systems

2. France - 1977 Energy saving decree - requires mandatory energy inspection in industry
(3) Italy - 2001 Energy efficiency decree - linked to liberalisation, it requires distribution utilities to implement an energy saving program with quantified, progressive annual targets

(4) EU motor efficiency labels - devised by the European Committee of Manufacturers of Electrical Machines and Power Electronics, and the European Commission

(5) US EPAct - the Energy Policy Act describes the minimum standards for energy efficient motors

(6) US NEMA Premium - the National Electrical Manufacturers Association labels high efficiency motors.

5.2 Information, education and shop floor assistance

(1) EuroDEEM - the European database of efficient electric motors

(2) EEBPp - the UK government's Energy Efficiency Best Practice Programme

(3) Efficient Compressed Air Systems 'Druckluft Effizienz' - a German programme to inform users about savings potentials in compressed air systems

(4) European Guide to Pump Efficiency - a first example in Europe for classification and labelling of pumps.

5.3 Financial incentives

(1) ECA - Enhanced Capital Allowances by the UK government.

5.4 Integrated programs

(1) Sparemotor - The Danish government gave subsidies for high efficiency motors as part of a larger campaign

(2) Polish Efficient Motor Programme (PEMP) - supported by the United Nations and Global Environmental Facility, this programme includes dissemination, demonstration, financial incentives and definition of regulation.

(3) As can be seen from the list above, there are only a few programmes that address motor systems. Most programmes focus on the motor, as motors alone are much easier to handle and to understand but, at the same time, many and far larger saving opportunities are missed by failing to take the motor system approach.
6 Conclusion

Realising the savings potential of 202 TWh for the EU would benefit European industry, society as a whole, save up to €10 billion a year and contribute to EU energy policy objectives. However, without action by government this potential will not be realised, despite strong economic drivers. The market will not deliver energy efficiency because of technical and managerial barriers explained in Section 3.

The possible solutions are well known and have been demonstrated in the market place. The optimal mix of actions includes regulation, financial incentives and information campaigns. Because of the excellent financial pay-back, both government and industry can justify a large-scale investment to realise this savings potential.

(1) Along with the direct financial benefit of saving energy, a saving of €6 billion per year can be made for European society in reduced environmental costs (EU-25, calculated using the EU-15 fuel mix). Allowing industry to trade the greenhouse emissions for improved energy efficiency could be a good measure; this measure alone would internalise about a third of environmental costs.

(2) High efficiency motor systems also bring secondary cost benefits to industry through reduced maintenance costs and improved operations. These savings can be estimated at €5 - 10 billion per year.

If we take into account an annual avoided cost of only €16 billion (electricity saving and avoided environmental pollution), and require a 3 year pay-back time, this results in a investment potential of €48 billion, spread over the next 20 years.

The following opportunities are available to promote efficiency in motor driven systems in the near future:

- Promotion of phase 2 of the Motor Challenge Programme by equipment manufacturers, energy agencies and other stakeholders
- Establishing world-class standards for efficiency as an implementing measure for the new Ecodesign Directive on Energy-using Products
- Defining energy efficiency in motor driven systems as best practice for complying with energy efficiency requirements in environmental permitting procedures.

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US Motor Market Status Report

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Abstract

This paper will update the European motor community on the status of the premium efficient motor market in the USA. The paper will discuss three elements of the premium motor market.

1) Acceptance of the NEMA Premium motor standard including recent metrics and penetration figures as released from NEMA.


3) Updates on recent legislation relating to motor efficiency.

1 Current motor regulations and NEMA Premium

Motor efficiency regulations were written into federal law in the United States beginning in 1992 with passage of the Energy Policy Act. The intent of the law was to establish specific levels of efficiency along with labeling and test standards for both initial efficiency determination and possible enforcement actions. The motor manufacturers had long held the premise that a natural market transformation would occur over time as the end user motor customer realized the saving potential of more efficient motors. In 1991 there was little conclusive evidence that the motor market was in fact shifting to the more efficient products that were available in the market. As a result several states began to explore motor efficiency regulations. The movement to regulate at the state level moved very quickly to the national level and motor manufactures were invited to testify before the US Congress regarding the impact of efficiency regulation.

The consequences of possible state legislation were not lost on the motor manufacturers. While none of the US companies wanted federal regulation of their product, none wanted to deal with the potential of 50 states trying to regulate motor efficiency. From the onset, US motor manufacturers chose to utilize as much existing data and standards as possible. On the recommendation of NEMA, the nominal efficiency levels from MG 1 were not only adopted in the rules, they were actually written into the legislation. Motor nameplate labeling added the NEMA nominal levels allowing users to clearly see the motor efficiency level on each unit. Test methods and procedures were taken directly from IEEE 112 Method B, which has been the US motor industry standard form many years.

The motor manufacturers intent was to draw upon the existing standards and procedures as much as possible to eliminate confusion in the market with motor customers. The goal was met. With the help of the Department of Energy public hearings were held allowing several special interest groups to provide input to the final rule making process. Armed with this information the staff at the Department of Energy was able to
document the regulation in a manner that allowed motor manufacturers to comply and
motor users to benefit from more efficient products and reduced energy usage.

The extent of product covered by the legislation is limited to 1-200 horsepower 2, 4, and
6 pole general purpose motors usable on 230/460 volt 60 hz systems. Actual imple-
mentation of federal regulation has affected approximately 65% of the total number of
units now sold in the USA. The remainder of the units sold are not considered “covered
product” and continue to be manufactured as standard efficient.

NEMA Premium Motor manufacturers along with utility and state-run efficiency pro-
grams, motor service providers, the U.S. Environmental Protection Agency and the
Department of Energy recognized that additional savings opportunities existed by using
motors with efficiency levels above the federal regulation and by including a wider
range of product. Working in partnership with the Consortium for Energy Efficiency and
these other stakeholders, NEMA launched the NEMA Premium standard in 2001 (pre-
sented at EEMODS 2002 paper 112).

“The US Department of Energy has reviewed the NEMA Premium motors’ potential
energy savings over a ten-year period. The DOE has concluded that motors having a
20 to 30-year service life can significantly save end users money by reducing operating
cost as well as increasing up-time through improved reliability. Because an industrial
motor can consume 4-6 times its original cost in energy each year, the saving of even 3
to 4 percent is significant over the motor’s life. DOE estimates that NEMA Premium,
when applied by American industry, can reduce 80 million tons of carbon and 5,800
gigawatt/hours over ten years or the equivalent of 16 million cars.” Paper 112
EEMODS 2002

Once the NEMA Premium standard was developed and published there remained the
task of market transformation. Motor manufacturers had worked to expand the product
range from 200 horsepower general purpose to 500 horsepower, special and definite
purpose, now the adoption rate of end users became the challenge.

Figure 1: 1 to 200 HP TEFC four pole motors
With the introduction of NEMA Premium motor users in the US now have two efficiency standards from which to chose. While the efficiency levels differ the labeling standard and test methods are identical. The development of NEMA premium was coordinated with leading power utilities allowing them to endorse all or part of the NEMA standard and utilize NEMA Premium for setting incentives and rebates efficiency levels.

2 The 1-2-3 Approach to Motor Management [talking to the accountants]

A critical issue we face as proponents of energy conservation using more efficient motor systems is communication with the financial side of business. Success or failure of our motor efficiency goals ultimately rest with prioritizing the capital necessary to implement efficient motor driven systems.

The resources required to effectively perform an energy audit can be substantial depending on plant size, motor population and difficulty to access. Various resources such as the local EASA shop, ESCO or motor manufacturer can be of assistance. End users have interest in cost reductions, but the cost and time necessary to perform an energy audit frequently present insurmountable obstacles that prevent necessary evaluation data. The 1-2-3 tool and process was created through the collaboration of several interested stake-holders who had come together as MDM [Motor Decisions Matter] The outcome of this process includes a sample of savings potential. A multi tab spread sheet that captures five representative motors from the installed population within the facility, uses energy costs including peak demand charges, operating hours and existing motor efficiency data or age, new motor net cost and installation costs to provide the evaluation.

Experience has shown that the migration from old lower efficient motors to NEMA premium can be divided into three potential savings options.

(1) Evaluation of a single failed unit to determine if a NEMA Premium motor is more beneficial than a federal efficient design.

(2) Evaluation of a single failed unit to determine if replacement with a new motor [NEMA Premium or federal level] is the more beneficial option.

(3) Evaluation of an installed base of multiple motors to determine if scheduled replacement is the most beneficial option.

Option three moves the decision from the factory floor to a management level. In doing so, the need for more detailed financial data is required. To make this move from technical input to financial output, the concept of sampling software coupled to standard financial data has evolved. It is the intent of this process to streamline the transfer of knowledge from electrical engineers and technicians to business managers who have the ability to take the input and place it with a much wider range of their business decisions. The 1-2-3 Approach creates necessary documentation to support these decisions by providing logical data in a summarized format that can demonstrate savings.
potential in a clear concise manner. It is not the intent of 1-2-3 to address the broader savings opportunities available from a systems approach.

The 1-2-3 Approach to Motor Management

“The 1-2-3 Approach, developed by MDM sponsors, is a good starting point for companies that might not have the resources to develop a motor management plan.

### Company Information

<table>
<thead>
<tr>
<th>Company Name</th>
<th>Contact</th>
<th>Location</th>
<th>Date Evaluated (mm/dd/yy)</th>
</tr>
</thead>
</table>

### Input: Representative Motor 1

**Motor Nameplate Data**

- Motor ID: kraft 1
- Manufacturer
- Model
- Size (hp): 30
- RPM: 3600
- Enclosure type
- Full-load efficiency(%): 85.5%
- Frame size and type
- Voltage rating
- Full-load amps

**Motor Application Information**

- Year motor installed
- Motor location
- Application
- Total yearly operating hours: 7,488
- Actual load (amps) (optional)
- Repairs/Rewinds
- Quantity of similar motors: 1

### Financial Information

- Cost of Electricity (note 1): $0.0800
- Desired Payback Period (yrs): 2
- Horsepower breakpoint (hp): 25

### Results: Representative Motor 1

<table>
<thead>
<tr>
<th>Current Costs (Base Case)</th>
<th>Replace Immediately with NEMA Premium</th>
<th>Replace with EPAct</th>
<th>Replace with NEMA Premium</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual Energy Cost</td>
<td>$15,680</td>
<td>$14,323</td>
<td>$15,680</td>
</tr>
<tr>
<td>Capital Investment</td>
<td>N/A</td>
<td>$1,438</td>
<td>$982</td>
</tr>
<tr>
<td>Incremental Investment Cost</td>
<td>N/A</td>
<td>$1,438</td>
<td>N/A</td>
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<tr>
<td>Annual Energy Savings</td>
<td>N/A</td>
<td>$1,357</td>
<td>N/A</td>
</tr>
<tr>
<td>Net Present Value</td>
<td>N/A</td>
<td>$2,517</td>
<td>N/A</td>
</tr>
<tr>
<td>Return on Investment</td>
<td>N/A</td>
<td>$6,70%</td>
<td>N/A</td>
</tr>
<tr>
<td>Simple Payback Period</td>
<td>N/A</td>
<td>1.06</td>
<td>N/A</td>
</tr>
</tbody>
</table>

### Decision: Representative Motor 1

Review the results with your customer. Decide on the appropriate course of action. Then, click the corresponding button and the 1-2-3 software will generate label(s) that you can use to tag this representative group of motors. It will also enter the dec

**Act Now**

- Replace Immediately with NEMA Premium

**Act Upon Motor Failure**

- Replace with EPAct
- Replace with NEMA Premium

Figure 2: 1-2-3 Motor data input screen
Using a limited amount of customer input, the tool estimates annual motor operating
costs and presents financial data for future decisions based on life-cycle costing. In this
way the 1-2-3 Approach user can make an informed decision on whether to repair or
replace a motor before it fails, and plan accordingly.

Making cost-effective choices consistently can reduce plant downtime, control future
operating and increase productivity.

Here’s what the 1-2-3 Approach can do

- calculate energy cost and potential energy savings
- calculate (and compare) the financial impact of repairing or replacing motors
- determine the payback periods for NEMA Premium motors
- calculate return-on-investment and net present value
- print tags that identify the best repair/replace options for each motor

Calculate energy cost and potential energy savings

Using the motor input tabs the factory maintenance or electrical staff records informa-
tion in the required cells the customer supplies required inputs and costs, nameplate
data including full-load efficiency, rewind will be required repair, motor efficiency main-
tained during repair for each of the five sample motors selected, as most representative
of the plant’s motor population. Users need to select sample motors that cover the
largest number of similar units operating within their facility. A large brewery in the cen-
tral US selected 15 horsepower pump motors used on over 50 similar applications in
their facility. Once data has been entered the a comparison is created giving a sum-
mary of the three motor efficiency categories, NEMA Premium, EPAct or repair of the
existing installed motor.

1-2-3 returns standard financial evaluations;
  Return on investment
  Net present value
  Simple payback
  Annual energy savings.

Savings over the motor’s life is a valuable tool used to determine capital expense by
demonstrating to the financial management the improvement to cash flow as the result
of improved motor efficiency. The 1-2-3 software has various default tables for depre-
cation and tax rates that can be adjusted by the user if facility conditions are not ade-
quately represented by the defaults.
Company Information

Company Name: Nestle
Location: St Louis MO
Date Evaluated: 06.11.04

Assumptions

Discount rate: 5%
Depreciable life: 5 years
Year
1
2
3
4
5
Depreciation schedule: 26.0%, 32.0%, 15.0%, 17.5%, 11.5%
Taxes rate: 39%

Application Information

Motor ID
Size (hp)
RPM
Quantity of similar motors
Gross Connected Horsepower
Cumul. yearly operating hours
Cost of Electricity
$0.060

Act Now: Replace Immediately with NEMA Premium

Cumulative Cash Flow

Year
Yr0
Yr1
Yr2
Yr3
Yr4
Yr5
Cumulative Annual Energy Savings
$17,051
$17,051
$17,051
Cumulative Debt Service *
0
0
0
0
0
Cumulative Operating Profit
1,740
1,793
5,889
10,279
10,279
Cumulative Income Tax
699
699
2,286
4,009
4,009
Cumulative Net Operating Profit After Tax
1,041
1,094
3,597
6,270
6,270
Cumulative Depreciation (Add back)
15,311
18,845
11,189
6,772
6,772
Cumulative Incremental Investment

($58,890)

Cumulative Cash Flow

($58,890)

$16,373

$17,751

$14,765

$13,043

$13,043

Cumulative Cash Flow To Date

($42,517)

($24,766)

($10,001)

$3,041

$16,084

Results

Cumulative Net Present Value
$6,198

Average Return on Investment
9.13%

Average Simple Payback Period (years)
3.45

* Attributable to Incremental Investment

Customer understanding and approval of all data input is critical to the 1·2·3 Approach. All calculations are based on incremental investment cost.

Figure 3: 1-2-3 Five year financial summary screen

The 1·2·3 Approach to Motor Management:
Motor Inventory

Company Name: Nestle

Representative Motor

Motor Application Information

Year motor installed
1964
1980
1978
1975
1982
Motor Application
Compressor
Discharge
Chipper
Mixer
Centrifuge
Total yearly operating hours
6,000
2,500
3,600
8,000
6,500
Actual load (amps) (optional)
85
20
125
195
75
% of Full Load (if available)
78.5%
97.0%
86.2%
97.2%
89.3%
Repairs/Rewinds
2
2
2
2
3
Quantity of similar motors
30
50
10
5
10

Figure 4: 1-2-3 Sample inventory summary screen
Once the 1-2-3 data has been presented to the financial decision makers in the business there is a need to address operations managers and the issues they have with changes to the motor system and population of replacement motors. Figure [4] shows the 1-2-3 sample inventory sheet. The inventory of spare motors will be adjusted based on the replacement decisions made as a result of the efficiency comparison and evaluation. Actual inventory requirements will vary with specific applications and predicted motor failure rates within the operation.

The 1·2·3 Approach to Motor Management:
Summary

<table>
<thead>
<tr>
<th>Company Information</th>
</tr>
</thead>
<tbody>
<tr>
<td>Company Name</td>
</tr>
<tr>
<td>Contact</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>1·2·3 Service Provider Information</th>
</tr>
</thead>
<tbody>
<tr>
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<tr>
<td>Phone</td>
</tr>
<tr>
<td>Contact Name</td>
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<tr>
<td>E-Mail</td>
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<table>
<thead>
<tr>
<th>Summary of Results</th>
<th>Sample Motor</th>
<th>Grand Total</th>
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<tbody>
<tr>
<td>Location</td>
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<td>Line #1</td>
</tr>
<tr>
<td>Date Evaluated</td>
<td>06.11.04</td>
<td>06.11.04</td>
</tr>
<tr>
<td>Quantity of Similar Motors</td>
<td>30</td>
<td>50</td>
</tr>
<tr>
<td>Gross Connected Horsepower</td>
<td>1500</td>
<td>1000</td>
</tr>
<tr>
<td>Cumulative Yearly Operating Hours</td>
<td>90,000</td>
<td>125,000</td>
</tr>
<tr>
<td>Cumul. Current Annual Energy Cost</td>
<td>$230,194</td>
<td>$135,636</td>
</tr>
<tr>
<td>Decision</td>
<td>Replace with NEMA Premium at Failure</td>
<td>Replace with NEMA Premium at Failure</td>
</tr>
<tr>
<td>Cumulative Capital Investment</td>
<td>$58,990</td>
<td>$36,700</td>
</tr>
<tr>
<td>Cumulative Annual Energy Savings</td>
<td>$17,051</td>
<td>$15,314</td>
</tr>
<tr>
<td>Average Simple Payback Period</td>
<td>1.10</td>
<td>0.63</td>
</tr>
<tr>
<td>Average Return on Investment</td>
<td>58.4%</td>
<td>78.6%</td>
</tr>
</tbody>
</table>

The Bottom Line

To improve the efficiency of the representative motors in your facility, IN VEST $220,305

In energy costs each year, your organization could SAVE $79,311

Over five years, these annual savings could total $396,557

And the average RETURN ON INVESTMENT based on incremental costs for this project would be 65.2%

Notes

1. The 1·2·3 Approach is a demonstration tool used to identify potential energy and operating cost savings. It does not guarantee that the identified savings will be realized.

2. These results are provided with the understanding that the customer must either provide or give his consent to all the data used in the 1·2·3 Approach.

3. These results are based on nameplate data which may not reflect the actual operating conditions of the motor.

Figure 5: 1-2-3 Financial summary screen
The final summary from 1-2-3 provides one of the best demonstration tools of any energy calculator. The summary clearly presents the cumulative values for investment, energy savings as well as averaging simple payback and return on investment for the motors sampled. With any luck, the benefits of improved motor efficiency, has been communicated and capital allocated for motor replacement. 1-2-3 is free software available at www.motorsmatter.org

3 Legislation

The US motor regulations have now been in effect for over seven years. Sixty three compliance numbers have been issued by the Department of Energy to motor manufacturers from all over the world. Each compliance numbers covers a brand of motors, allowing a single manufacturer to apply for and receive multiple numbers. Over half of the compliance numbers have been issued to cover motors imported from outside the US. The DOE has not reported any infractions of the federal energy standard for motors. Nor have there been any challenges or examples where the DOE implemented the enforcement testing procedure. DOE has had improper compliance data submitted and has requested manufacturers to resubmit the data.

A DOE energy study of small motors [48 and 56 frame] has been completed. The study concludes the savings potential available from regulating small motors due to their limited hours of operation and limited saving per unit makes regulation unlikely due to a lack of economic justification. NEMA has asked the DOE to publish their rule in support of the reports findings. As of this writing DOE has not issued a final report covering small motors.

“NEMA agrees that a determination should be a high priority. NEMA believes that DOE should promptly publish a determination that regulating small (fractional horsepower) motors would not save significant amounts of energy and therefore rulemaking is unwarranted. DOE numbers for energy savings show that regulation is unwarranted (only at the high end of DOE estimates with high numbers of future motor sales would savings approach 1Q). NEMA believes that the actual savings would be less. The DOE determination should clearly state that small motors are “covered equipment”, so as to unambiguously preempt state standards.” NEMA position July 2004

Currently the US Congress is moving forward with a comprehensive energy policy bill which covers a wide range of issues. This bill includes language that will require all federal facilities to adopt the NEMA Premium motor efficiency standard as the only replacement motor to be used. This new rule is expected to take effect within the first year of passage. This regulation will only affect those motors used in federal facilities, any impact on industrial or commercial applications will be de facto. The energy policy act will also include energy savings incentives for commercial buildings. These incentives will focus on a broader systems approach, which should have an impact on demand for NEMA Premium motors. However the systems integration design to optimize efficiency does not specify the components to be used.
Conclusion

The Federal energy standard for motors has increased the efficiency of integral horsepower motors sold in the US over the past seven years. Manufacturers in the US have worked with a variety of stakeholders to create an even higher standard that has been endorsed by utilities and government agencies. Working together with a coalition of stakeholders, new tools such as the 1-2-3 Approach to Motor Management have been created to bridge the technical/business communications gap between engineers and financial managers and promote the adoption of proactive motor management strategies including NEMA Premium. Manufacturers in the US build and ship products that meet minimum federal efficiency regulations as required by law. These products cover approximately 65-70% of the units sold in the US. In 2003 NEMA Premium motors shipments were approximately 20% of all 1-500 HP motors sold. [need to rewrite this section for clarity- see comment] The remainder of the motors shipped in the US, were special or definite purpose designs that were not covered by Epact nor were they built as NEMA Premium. NEMA manufacturers project continued growth of NEMA Premium motors sales as more tools, standards and policies base motor efficiency on the standard. Motor manufacturers do not support or expect additional regulation of electric motors in the US market. Manufacturers do support system efficiency programs and will continue to play an active role in their development.

Figure 6: Over 310,000 NEMA Premium units shipped in 2003 or nearly 20% of the 1-500 HP US motor market
References


Swiss Activities in Motor driven Systems and the Voluntary Agreement of the Swiss Industry

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Abstract

In order to promote the efficient use of electricity, the Electricity Research Programme of the Swiss Federal Office of Energy focuses a great deal on electric drives and motors. More than 45% of the electricity use in Switzerland is consumed by electrical motors. More than 5'000 GWh of electricity annually consumed could be saved if motors and drive systems were designed from an energy efficiency point of view.

The focus of activity is on the optimization of drive systems (compressed air systems, pumps, lifts, etc.) and on the promotion of efficient technologies (frequency converters/integral drives, design and dimensioning tools, etc.).

Efforts are also being undertaken in cooperation with the relevant industry to eliminate motors from the market with low levels of efficiency. Similar to the voluntary agreement which the European Commission and CEMEP have signed, the Swiss Industry has in a joint initiative with the Swiss Federal Office of Energy agreed to save energy and to increase the market share of the efficient motors of the type eff1 in the future to 19%.

1 Introduction

Electricity plays a vital role in all areas of daily life. With a proportion of around 20 % to overall end energy demand, it is of central economic importance. In order to promote efficient use of this valuable source of energy, the Electricity Research programme of the Swiss Federal Office of Energy focuses a great deal on electric drives and motors. This is in line with the strategy of the country-wide Swiss Programme SwissEnergy which focuses on different areas to promote and realize energy efficiency and renewable energy sources. One goal of the Programme SwissEnergy defines is to limit the increase in electrical consumption to not more than 5% in 2010 in comparison to 2000. As the newest statistical figure of end 2004 shows - this increase is already about 7,4% - it will be extremely difficult to reach the defined goal. Therefore all possible efforts have to be made to bring more efficiency in the electricity area.

It is well known that in the area of the electric drives and motors a substantial efficiency potential is available. It has been pointed out in several studies that in the area of electric drives and motors, energy-related activities should be aimed not only at optimizing motors, but also at improving the energy efficiency of the entire drive systems. More than 45% of the electricity use is consumed by electrical motors. More than 5'000 GWh of electricity annually consumed could be saved in a cost effective manner if motors and drive systems were designed from an energy efficiency point of view.
2 The Swiss Electricity Research Programme

The Swiss electricity research programme is one of several specific research programmes of Switzerland. The overall goal and the frame of all programmes are defined by a supreme Federal Research commission in a strategic research concept every four years.

As it is well known, there are significant saving potentials in the area of efficient electricity use and this is therefore where the priority in the programme lies. Three priorities have resulted on the basis of estimates of efficiency potentials and co-ordination with research efforts elsewhere: electric drives and motors / information and communications technology / electrical appliances. Only to complete the picture, it has to be mentioned that distribution and storage of electricity are as well areas in which the programme acts.

It has been pointed out in a variety of studies that in the area of electric drives and motors, energy-related activities should be aimed not only at optimizing motors, but also at improving the energy efficiency of entire drive systems. According to estimates presented in recent studies, this could result in a reduction in the power consumption of electric drives and motors by approximately 20%. The focus of the activities therefore is on the optimization of drive systems (compressed air systems, pumps, lifts, etc.), and on the promotion of interactive technologies (frequency converters/integral drives, design and dimensioning tools, etc.). Efforts are also being undertaken in cooperation with the relevant industries to eliminate motors from the market with low levels of efficiency.
In the area of information and communications technology (including automated appliances), faster progress needs to be made with regard to efforts aimed at reducing or eliminating standby losses and at lowering electricity consumption in normal operating mode through technological, regulatory or other measures. Here, a variety of complementary efforts are being made in close co-ordination and consultation with international committees.

In the area of appliances, a variety of activities are being supported, especially those concerning household equipment. Here, appliances are to be promoted that are efficient both in normal operating mode and standby, though the topic of networking is steadily gaining in significance.

3 Programme Activities related to motors and drives

3.1 General goal of the activities

The largest numbers of motors which are in use are standard motors in the range of about 1 to 22 kW. Therefore, this range of motors is from an efficient point of view interesting to cope with.

The programme focuses on the following goals:

- Optimization of defined and closed drive systems (e.g. compressed air system, lift system, pump system), best practise-projects
- Introduction and promotion of Life Cycle Cost aspects (LLC)
- Supporting of new ideas, concepts and technical solutions for improving the energy efficiency
- Promotion of the Integraldrive / variable speed drive
- Development and promotion of software based tools to optimize dimension of motors
- Voluntary agreements with industry
- International cooperation (coordinated projects, labelling, agreements, conferences)

3.2 Selection of projects

Several motor specific projects are described below in a summarizing way. One has to be aware that this is only a selection as many more activities have been done in the past. Further information of additional projects as well as of all mentioned projects corresponding reports can be downloaded from the Internet (see references).
3.2.1 The Compressed Air Swiss Campaign

In Switzerland 150'000 compressed air units use approximately 750 GWh electricity which is about 1.5% of the annual national consumption. In industrial companies compressed air units require up to 25% of the operational current consumption. In Switzerland theoretically 300 GWh and practically 100 GWh electrical current per year could be saved with energy-efficient compressed air units.

As well as Germany realized the campaign “druckluft effizient”, Switzerland intends to launch a similar campaign in the framework of SwissEnergy and with a heavy involvement of the appropriate industry. It will last 3 years starting 2005 and consists of several modules. The main activity consists of promotion and information.

![Energy Flow of a compressed air system](image)

Figure 2: Energy Flow of a compressed air system (Source: Swiss Federal Office of Energy)

3.2.2 Compressed Air in a Weaving Mill

A cotton weaving mill with 121 weaving looms used 180'000 kWh of electricity per year with a new 30 kW screw compressor. A load analysis resulted in constant capacity from Sunday evening to Saturday noon of 28 kW. On work-free Sunday the compressed air unit was switched off. By way of trial the compressor was operated on Sunday, the capacity amounted to 22 kW. In the weaving room one heard escaping air which proceeded from broken-shaken armatures from standing machines. In the usual operation procedure these leakages could be never noticed because of the loud engine noises. The repair of the air armatures reduced the current consumption of the compressed air unit by 70% and paid for themselves in energy savings within few months.

3.2.3 Compressed Air in a Carpenter’s Workshop

A modern carpenter's workshop for kitchen furniture with 20 employees which was analysed, uses approximately 140'000 kWh of electricity per year, whereby the compressed air unit requires 10% of the current consumption. The consumers consist of 5 automatic machines (40%), various hand attachments (40%) and leakage (20%).
compressed air supply takes place to 90% via 5.5 kW a screw compressor and to 10% via 5.5 kW a piston compressor. Without the already available time switch which switches the compressed air unit off outside of the work time, the current consumption 25'000 kWh per year would be higher. By the optimization at the screw compressor (operating mode start-stop, reduction of the pressure level, reduction of the slowing-down time, maintenance) the current consumption could be reduced to 8'400 kWh/a which corresponds to a saving of 40%.

![Diagram of compressed air system](image)

**Figure 3:** Simplified Scheme of production and distribution of the compressed air system (Source: Final report of corresponding project)

### 3.2.4 Motor drives at the Sawmill Industry

The annual electricity consumption of the sawmill industry amounts approximately to about 80 GWh in Switzerland, based on the quantity of the processed wood and projected with power consumption numbers. If one assumes that 10 to 20% current saving can be reckoned in accordance with different test results, then there exists a substantial potential for savings of about 8 to 16 GWh per annum in this industry. This potential arises in case of a replacement of installations with a consistent use of energy-saving solutions and technologies. In order to fully exploit the potential of 10 to 20% current saving it must be reckoned with amortization periods of approx. 5 to 15 years.

Representatively of the sawmill industry Schilliger Holz AG is analysed more exactly as a case example having an electricity consumption of almost 6 GWh (in 2001). In this project energy-saving measures are suggested which show economic amortization periods of approx. 5 years. By realizing these measures, savings of approx. 400 MWh/a will arise - corresponding to approx. 7% of the total current consumption of Schilliger Holz AG. The investment costs are approx. CHF 200’000.--, the annual sav-
Many electric motors are left running in a sawmill even while not being needed/used. These idle running hours arise from the production conditions (e.g. production cycles) or from inattention to machine operation requirements. These idle hours can be reduced by technical and primarily by organizational measures.

An electric motor in no-load operation needs only a fraction of the power indicated on the rating plate. The situation is completely different in case of suction-air or compressed-air plants. When e.g. suction-air plants are operated under no load, condition air is still transported whereby even in the absence of chips or shavings the same power is needed by the motor. The greatest reduction potential occurs with these kinds of plant.

The following lists factors which yield an energy optimal operation in a sawmill. The data in the square brackets show the saving per year related to the appropriate unit (e.g. what can be saved in the field of the compressed air for Schilliger Holz AG).

- Production and distribution of compressed air with low pressure, low-pressure drop, few leakages and with shutting-off of sectors in the distribution system [380 MWh, 50%, CHF 40'000.--]
- Production of compressed air meeting demand and with good part-load behaviour (without no load running periods) [100 MWh, 15%, CHF 10'000.--]
- Suction-air systems equipped with automate shut-off valves at the suction places, fans driven by frequency converter [291 MWh, 49%, CHF 33'600.--]
- Feedback of the output air of the suction-air systems into the production room [3.5 MWh, only electric energy without heat energy]
- Optimized heat production and distribution (meeting the demand and load dependent, e.g. with quantities of water)
- Use of frequency converters for the fans of the drying chambers [112 MWh, 24%, CHF 12'600.--]
- Equipping the drying chamber with heat recovery/regeneration for the output air and adopting good thermal insulation of the chambers
- Automatic or manual switching of power consuming devices in order to meet demand (motor is only running when it is used!)
- Decrease of friction at conveyors (e.g. conveying belts, conveyor chains etc.)
- Instructing employees, incorporating energy-saving as one of the business aims and ensure that management and staff are aware of the long-term financial benefit of energy-saving
3.2.5 Project Stepper Motors

Stepper Motors are powerful and efficient. They are manufactured within a torque range from 0.01 Nm up to 100 Nm. The most popular range is 1 Nm. Approximately 600,000 stepper drivers are sold in Switzerland every year. They are built in production facilities and equipped with simple drivers using special IC’s from dedicated manufacturers.

In order to increase operational safety, the motors are normally driven with 80 to 100% of their nominal current. Current reduction possibilities often will not be taken into consideration. The energy saving stepper drive is controlled the way that current flows only if the motor really needs the torque.

With standard servo components of „LEAG Antriebstechnik AG“ the speed of 1’300 RPM was reached. A new commutation electronic was developed using a 75 MHz RISC microprocessor and an optimized current control to reach the requested 3’000 RPM. The power consumption measurements between the novel drive unit “New Stepper” and a conventional stepper amplifier showed a 50% input energy reduction.

The amortization of the additional costs due to the energy saving of 100 W installed power is possible within 8 to 12 month.

The advantages are:
- To halve the energy consumption
- To increase the operational safety
- To increase the motor dynamic
- To double the thermal reserve of the drive or to reduce equipment costs.

3.2.6 Motor Challenge Programme (MCP)

The main aims of the pilot project associated with the Motor Challenge Programme (MCP) initiated by the European Commission (Transport and Energy Committee) were to create the prerequisites for subsequent implementation of the programme and to carry out trials during the difficult stage of establishing contact with industrial companies and initial energy audits. Switzerland participated in this pilot project which was concluded after a period of two years when the Motor Challenge Programme itself was launched in February 2003. The programme focuses primarily on compressed air, pump and ventilator systems, as well as on comprehensive motor driven systems. A specific module that contains both technical and contractual information was defined for each priority area. Companies may become involved in the programme either as partners (users of drive systems) or as endorsers (suppliers, planners, etc. of such systems).

Thanks to the support of the Swiss Energy Agency for Industry, two companies in Switzerland (a food processing group and a major chemical pulp producer) agreed to participate in the programme. An audit was carried out by experts from the Swiss Motor Challenge Team in order to identify the most suitable areas for efficiency measures.
and define according MCP modules. Efficiency potentials of around 3 GWh/a were identified and these represent a high proportion of the estimated total of 18 GWh/a in the overall programme.

Switzerland will cooperate with the launched official MCP and will establish an appropriate Swiss project organisation.

3.2.7 The Lonza-Project

The Lonza AG chemicals factory in Visp/Lalden is one of the largest consumers of electricity in Switzerland (almost 1% of the entire electricity consumption). At Lonza, electricity is primarily used for driving electric motors (94% of its total consumption) which mainly power electric pumps (44% of consumption) and compressors (38%).

Regarding the final consumer’s use of the energy, there is a substantial saving potential. Considerable potential for saving electricity exists in all installations and can be beneficially utilised. The estimated utilisable potential in systems that are permanently in operation and use small-scale consumers is 10% to 30%, especially if operating times are reduced and pumps are optimally designed. The estimated utilisable potential in systems that use large-scale consumers is 5% to 20%, especially if the system is operated at the optimum efficiency level or if it is configured for flexible use (partial load operation).

Potential can best be utilised during the planning stage for new systems (systems engineering). However, it should be born in mind that designing a system entails a careful balance between detailed knowledge of the future installation, flexibility, standardization and reserves as well as planning costs and energy efficiency.

It would be possible to bring about more energy-conscious planning of systems by sensitizing project engineers. In existing systems, utilisation of available potential is considerably more complex and in view of the already existing components does not offer the same economic benefits since it would be associated with much greater outlay on the part of systems and operations engineers. The various measures that have been implemented show (alongside any necessary adjustments to the system) that for each Swiss franc of annual electricity costs that is saved, 1 to 2 additional franc has to be spent on engineering measures (i.e. hard-earned savings!).

Savings in energy consumption recur each year and remain effective until the end of the service life of the system concerned (sustainability). Over the next few years they will grow considerably more important due to regulations restricting CO2 emissions (CO2 Act), quantities of cooling water, etc. In view of the results of the project, a new position called “Energy Challenging” was created in February 2002 with the following Job description: Enhance the energy efficiency of selected appliances, support the planning of new investments, support systems operators with the optimization of existing installations, increase sensitization on the part of planners and operators through training and further education.
The following example shows one success of the work of the Energy Challenging person. Within the Niacin-production (Vitamin B) it was possible after having studied the process to install a specific heat exchange system. With this the origin steam production was reduced about 42,000 MWh a year. A second heat exchange system and additional measures resulted in an additional annual saving of about 72,200 MWh.

4 The Swiss Motor Voluntary Agreement

Similar to the voluntary agreement which the European Commission and CEMEP have signed, the Swiss Industry has in a joint initiative with the Swiss Federal Office of Energy agreed to save energy committing itself to ambiguous targets. The agreement contains the following motors, which are in line with the definition of the types eff1, eff2, eff3:

- Fan ventilated (IP 54 or IP 55) three phase A.C. squirrel cage induction motors 1.1 to 90 kW
- 2- or 4-poles, rated for 400 V-line, 50 Hz
- Duty Class S1
- Standard design.

Table 1: The following targets have been agreed to be reached by industry:

<table>
<thead>
<tr>
<th>Year</th>
<th>2003</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
</tr>
</thead>
<tbody>
<tr>
<td>Share eff1 of total delivered eff1, eff2, eff3</td>
<td>8%</td>
<td>11%</td>
<td>13%</td>
<td>15%</td>
<td>17%</td>
<td>19%</td>
</tr>
</tbody>
</table>

Fig. 4: Signing act on December 17, 2004, with (left to right) W. Stalder (Industry Association SAP), W. Steinmann, (Director of the Swiss Federal Office of Energy), P. Mazenauer (Industry) (Source: Swiss Federal Office of Energy)
5 Conclusion remarks

All the mentioned industrial projects show that substantial energy savings in the area of motor driven systems can be reached. They not only prove that the energy potential is huge, but also that energy efficiency is economical. And with the voluntary agreement there is a commitment of the supplying industry to promote actively the high efficient motor.

To further promote this energy saving actions, the national programme SwissEnergy intends to define together with the Swiss Energy agency of the industry national wide actions to promote the energy efficiency of motors. The details are still in elaboration but the results of the presented projects will certainly be stimulating.

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Activities to Improve Energy Efficiency Motor Systems in Spain

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Abstract

This paper outlines the Spanish situation in the field of the energy saving and efficiency. It shows the main characteristics of a Plan elaborated in 2003 by Energy Authority and denominated “Spanish Strategy for Saving and Energy Efficiency”. We summarize the motivation and main goals of Plan. Also it is indicated the main lines that are needed to promote efficiency in electric motor systems in Spain. With this paper we want to emphasize the attention about the convenience to start some initiatives to increase energy efficiency in electric motors. Finally, we expose the summary of a research project designed by paper authors to be implemented in a Spanish north region to show the electric motor systems opportunities.

1 Introduction

Motor systems consume 50% of the world’s electricity (E-Source Inc. 1999). In some country, Canada, this value is more than 75% of a plant’s electricity (Office of Energy Efficiency of NRC 2001). Motors drive all types of process equipment and have a direct effect on operation’s productivity and product quality. Improved energy efficiency helps industry lower operating costs and be more productive. Often, improving the efficiency of an electric motor system will uncover solutions to a many production and maintenance problems. A motor system is defined as including all the components from the initial energy input to the final process use. Energy use defined in this way reflects the power consumed per unit of product produced. Management of the motor system involves maximizing the value of capital assets and minimizing operating costs, while maintaining efficient and reliable production output. Typically, the value derived from these benefits is more significant than the energy cost savings. Benefits can be obtained in the areas of productivity, reliability and cost reduction. Any country must consider this subject because there are a lot of benefits with improvement in energy efficiency.

2 Spanish strategy for saving and energy efficiency

The convenience of the mentioned strategy is justified by the high relative growth of the consumption of primary energy in Spain in relation to the growth of the GDP. Between 1975 and 1990, the primary energy consumption increased in Spain to an annual average rate of 2.7%, whereas in the 1990s it has increased 3.1% annually, with greater growth in second half of the last decade. This increase has been much higher than the increase registered by the GDP, resulting in an upward trend in energy intensity (energy consumption/GDP relation) represented in Figure 1.

![Energy Intensity Graph](image)

**Figure 1: Primary energy intensity (Ministry of Economy - Spanish Gov. 2003)**

The explanatory factors of this evolution of the energy intensity are the following ones:

- The reached improvements in the household-electric equipment that normally contribute to increase in the energy consumption.
- Significant rise of the use of autos for transport (higher than the European average)
- Low energy prices, result of the new policies of the power markets, does not prevent but they add certain complexity to the adoption of measures of improvement of the energy efficiency.

In addition to these considerations, it is necessary to indicate that in the European countries context, Spain it is located in an intermediate level. The intensity indicator shows recent tendencies of convergence (for average values in period of time 1985-2000) towards the existing average values in the European Union (around 0.20 ktep/ECU of year 1995) in coherence with the social and economic evolution before commented. It is reflected in figure 2.
2.1 Goals of the Plan

The primary target of the Plan is the modification of the consuming sectors behavior, forming a new scenario of forecast that is defined as Forecast of Efficiency. Assuming the objectives of efficiency and saving are fulfilled (by applying the measures anticipated for each one of the implied sectors) it is obtained the results that are indicated next.
Figure 3 shows in two scenarios the sector distribution of the final consumption of energy anticipated for 2012. The Scenario Base was used like reference in 2002, for details go to (Ministry of Economy - Spanish Gov. 2003). The saving objectives that, logically, correspond with the difference between the Scenario Base and Scenario of Efficiency, in 2012, ascend to 9,824 ktep. In relative terms this saving supposes 10.8% of the consumption of final energy in Spain in 2000.

Industry, the sector directly related to the efficiency in Electric Motor Systems, is the one that displays the greater reducing objective (relative values), because it is the sector that has introduced more improvements of efficiency and that more has controlled the growth of the energy consumption. However, the anticipated saving of the sector is important although with a significant level of public aids.

The global objectives of final energy consumption in the industry sector, in the Strategy horizon, are gathered in the following table.

<table>
<thead>
<tr>
<th>2000</th>
<th>2006</th>
<th>2012</th>
<th>Growth per year (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ktep</td>
<td>%</td>
<td>ktep</td>
<td>%</td>
</tr>
<tr>
<td>Industry</td>
<td>34.340</td>
<td>38,0</td>
<td>40.432</td>
</tr>
<tr>
<td>All sectors</td>
<td>90.266</td>
<td>100,0</td>
<td>110.157</td>
</tr>
</tbody>
</table>

In the 2004-2012 period the Strategy of Saving and Power Efficiency anticipates annual savings of 2.351 ktep for the industrial sector, with investments of 2.161.000 thousands of euros. The public support is 38,9% (respect to the total investment) and a save/investment per year of 1,09 tep by each thousand euros.

The commented strategic plan anticipates a total investment of 25.993.000 thousands of euros. With this action it is hoped to obtain a saving in the cost of the primary energy of 2.862.000 thousands of euros. The amounts related to the improvement in the efficiency in the electric motor systems are not specifically displayed.

At the moment this energy plan is put under debate. It is quite possible that the plan will be modified for reasons of economic opportunity and recent political change with new government established at March 2004. In any case, the organism of the Spanish administration that will carry out the development and the implantation of the measures for the promotion of the improvement in the efficiency of the electric motors will be the Institute for the Energy Diversification and Efficiency (IDAE).
3 The Institute for Energy Diversification and Efficiency (IDAE)

The Institute for Energy Diversification and Efficiency (IDAE) is a public company, depending on the Ministry of Industry, Tourism and Commerce, through the General Secretariat of Energy. Among its functions is the application of the initiatives of improvement of the efficiency of the electric motor systems.

The IDAE is born in 1974 with the name Energy Studies Centre, and after diverse stages, emerged as IDAE in 1984. The current mission of IDAE reflects changes from the Administration of the State (1986-1999-2002). In April of 2004 Spanish Administration assigned the IDAE’s mission: to promote energy efficiency and the rational use of energy in Spain, as well as the diversification of energy sources and the promotion of renewable energy.

The activities of the IDAE to increase the interest in the elevation of the power efficiency are:

- The promotion of the use of new technologies of saving and substitution in the industrial sectors, agricultural, services, houses, buildings and transport. Particularly, it will have to foment industrial projects of incorporation of variable speed drives in substitution of obsolete techniques of control of fluids, the use of motors of high efficiency, and the replacement of old and low efficient motors by other new ones.

- The management and accomplishment of the pursuit of the plans of national saving and power efficiency. In this function it will have to provide technical attendance and to contribute in the accomplishment of power audits.

- Promotion the rational and efficient use of the energy specially in the industrial sector.

- The collaboration with the European Commission in energy program management and with Spanish companies to obtain aids to apply these programs. In this point it is necessary that one leans to the industries in the participation in the present and future initiatives, like Motor Challenge Programme.

4 Main lines of performance for the promotion of the efficiency in electric motor systems in Spain

At present it appears in Spain a reduced public interest in the development of specific programs of application in electric systems motors. It is necessary an important impulse. Following the indications of experts (Nadel et al. 2002) it will be necessary to develop actions to specific products (motor, compressed-air systems, pumps and fans, air conditioning and refrigeration systems) and also actions in education and training, energy audits, technical assistance, financial incentives, and diffusion of information.

It is necessary to promote purchases of high-efficiency and premium-efficiency motors, to promote good motor management practices include automated inventory of motors...
and efficiency, predictive/preventive maintenance practices, guidelines for re-pair/replace decisions, stoking guidelines for easy replacement, and use of quality re-pair specifications. About compressed-air, pumps and fans systems it is necessary developing tools and training programs to allow distributors and their costumers to improve their systems.

On the other hand, we need a lot of resources in education and training. Motor efficiency should be incorporated into engineering and technicians curricula. To contribute in market transformation it is necessary training consumers and vendors by technical reports, and large collection of demonstrated examples like in Best Practice Program in the UK.

In order to achieve better use of energy in Spanish industry energy audits are essential to elaborate detailed engineering analysis that can be provided by several industrial audit programs operated by regional energy offices, universities and utilities. An example of this, is the proposal research project (Mantilla 2004).

5 Regional proposal for the promotion of the efficiency in the electric motors

In recent days we have presented to a public Spanish agency a proposal of work to improve energy efficiency in a north Spanish region, Cantabria. In the following lines we resume our objectives.

- To develop a present inventory of the drive systems based on the electric motor used in the industrial sector in Autonomous Community of Cantabria. The spread of inventory in its technological, sector and geographic characteristics is the following one:

We will take the systems that incorporate induction motors from 0,75 kW rated power (equal or superior) that are driving the main types of loads (pumps, ventilators, compressors and others). These criteria agree with the adopted ones in preceding studies (Almeida 1996), and reach to most of the installed motor systems in the industry (this type of motor approximately includes 90% of the installed motors) will classify the systems in ranks of power and types of loads.

The results grouped by categories of economic activity will appear, exposing separately each one. With this purpose the motor systems will be classified according to the industrial company that uses them, taking the CNAE criterion (Spanish classification of economic activities) restricted to the industrial sector and with a definition of reach to the second digit of CNAE number. The economic activities of greater electrical consumption will be selected for an individualized study, so that these mean at least 75% of the industrial electrical consumption of the region, the motor systems of the rest of economic activities will be considered in an only group.

The study is limited to Autonomous Community of Cantabria for the following reasons:
Cantabria constitutes an identifiable economic unit. The hoped results can be representatives for other Spanish regions with minor corrections in the procedure.

The economic financing asked for to the Spanish administration and the capacity of our investigation team determine a limitation in the work load. Cantabria is a small and representative Spanish region.

The objectives of this action are the following ones:

- To develop the detailed profile of the operating characteristics of the electric motor systems inventoried maintaining the previous criteria.

The characteristics of purpose of use of the motor system (type of load), the level of rated power, the number of hours of operation, the factor of load and the consumption of energy will be reflected. The natural year will be the common temporary reference for all parameters.

- To enunciate and to value the main opportunities of energy saving in the previous analyzed motor systems.

The opportunities to improve the efficiency of the characterized motor systems will be identified and enunciated. The recommendations to improve each motor system component will be indicated. The considered system elements, and therefore the smallest unit for the analysis, will be the following ones: power and control systems, electric motor, mechanical connection, driven machine, and loads.

The technical saving potential amount (without economic considerations) and the economic saving potential (economic considerations included) will be calculated, according to the criterion widely accepted of recovery of the investments in three years. These valuations will be applied to the two main opportunities of efficiency improvement, the use of high efficiency motors (HEM) and the use of variable speed drives (VSD).

The objectives of our proposal study are included in the priorities of the Spanish National Program of Energy, and faithfully develop concrete aspects of the thematic line denominated "Efficiency in the final use of the energy with the improvement of efficiency..."

Both objectives declared previously are evidently new targets because other analogous published results (nature and reach) does not exist in Spain, and particularly, in Cantabria. On the other hand, as far as the relevance of the objectives, we considered that proposal is of great interest by the power and productive indicators that contributes and because it constitutes a generating base of later investigating workings in different technological fields (energy). It must stand out, that the motor systems, by their importance, constitute a relevant element of any industrial production systems. The realistic knowledge of these systems contributes to very outstanding indices of valuation of the power consumption and the economic activity of productive sectors or geographic regions.
6 Conclusions

In summary, this study will allow to know in detail the implantation of motor systems. Next steps will be the following initiatives:

• Contribution to detailed engineering analyses for industrialaudit programmes that can be developed by regional energy offices and other organizations
• Promotion of technical assistance to previously selected industrial companies.
• Promotion of education and training to end-users and engineers in general.

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Polish Energy Efficient Motor Programme – PEMP

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Abstract

The economic potential for energy efficiency improvement of electric motor systems in Poland is large and could substantially reduce domestic greenhouse gas emissions. While industrial energy efficiency is a priority in Polish energy and climate change policy, the market share of energy efficient motors is currently very low due to a range of barriers. The Polish Energy Efficient Motors Programme (PEMP) aims to overcome these existing barriers. PEMP addresses key technologies and sectors identified by the Polish Energy Policy, with a special emphasis on the manufacturing industry, the energy sector (heating), the utility industry (water supply and sewage treatment) and the mining sector. Under the programme, four components are developed and implemented: capacity building by providing information and services, implementation of demonstration projects, market transformation using a financial incentive mechanism; and development of industrial energy efficiency policy.

1 Project background

With 38.7 million inhabitants and area of 312,000 square kilometers, Poland is considered a strategic country in Central Europe. Polish economic growth and social stability have served as a model for neighboring countries. During the last ten years, Poland has carried out fundamental and highly effective economic and social reforms, including the transformation from a central economy to an open market economy. After the social and economic shocks of the early 1990s, Poland has shown stable economic growth in GDP. From 1991 to 2003, GDP in Poland increased by 64,7 per cent (based on 2003 fixed prices).

Productivity, including productivity in energy use, increased significantly in the above mentioned period. As a result, primary energy productivity increased from 118,3 PLN/GJ in 1991 to 203,4 PLN/GJ in 2002. While GDP has increased over the past five years, electric energy production in Poland has remained constant. Nonetheless, Poland still has high energy intensity in comparison to OECD countries. For example energy intensity in 1998 in Poland (0.79 MWh/1000 USD) was approximately four times higher than in countries such as Germany, Switzerland, Denmark, and the Netherlands.

Power production in Poland relies on hard coal and brown coal. Ninety-five (95) per cent of electric energy is generated in coal-fired power plants, as well as in coal-fired heat and power stations. As a result, the share of carbon dioxide emission from electricity generation represents 38 percent of the country’s overall carbon dioxide emissions. In 2001, Poland’s annual CO2 emissions totaled 318 million tons of CO2. Of this, 38 per cent of the emissions came from electricity production, of which 50% were attributable to electric motor systems (i.e., 60 million tons of CO2 per year).
Electric motor systems (which include motors, drives, pumps, fans, compressor, and control equipment) use 40 to 50 per cent of all electricity consumed in Poland. The share differs by end-use sector: from 40-90 per cent in production sector to 20-40 per cent in households and public services. Manufacturing activities (35 per cent), electric energy, gas, heat and water supply (17 per cent) and households (17 per cent) constitute the biggest share of Poland’s electricity consumption, which totals 122.8 TWh annually.

The most significant application for electric motor systems (60 per cent of electric energy consumption) is for raising pressure and pumping liquids and gases through pumps, fans, compressors, etc. in three industrial sectors: the manufacturing sector; the energy sector (gas, heat, and water supply); and the mining industry. The technical potential for electricity savings of electric motor systems in these applications in these sectors is 3.9 TWh/year. The remaining 40 per cent of electricity consumption by electric motor systems is used by freight and passenger transport and for materials processing. Total technical potential for savings is estimated at 6.3 TWh/year (which is 5.1 per cent of overall electric energy consumption in Poland).

The economic potential for electricity savings of electric motor systems is 5.6 TWh/year for a payback period of less than 10 years, or 3.1 TWh/year for a payback period of less than 6 years. The payback period within the economic potential is a conservative measure that only considers electric energy cost savings. It does not consider additional benefits, such as the reduction of water consumption, air, and gas losses as well as automation and process management. Electricity savings of 6.3 TWh/year, or the total technical potential, would result in a reduction of greenhouse gases (GHGs) in Poland of 6.8 million tons of CO2 per year. This figure corresponds to 1.6 percent of Poland’s total GHG emissions in 1997.

2 Genesis of the project

Basing on facts:

- the technical potential for energy efficiency improvement of electric motor systems in Poland is large in both absolute and relative terms;
- energy efficiency increases could substantially reduce domestic GHG emissions in Poland, thereby supporting Poland’s activities as a party to the UN Framework Convention on Climate Change (UNFCCC);
- there is great economic potential for energy efficiency improvements with low payback periods that meet the usual investment criteria. However, manufacturers have reported that almost no energy efficient motors have been sold recently in Poland. Therefore, it is clear that these investments face substantial barriers;
- a large economic potential exists with higher pay-pack period, which could be exploited by financial incentives lowering the pay-back period;
the manufacturing industry, the energy and water sector, and the mining industry are key sectors, because they show the largest economic potential for efficiency improvements.

- lack of national promotional initiatives and lack of funding for such activities;
- finally good experience with PELP - Polish Efficient Lighting Project (transformation of market of energy efficient lighting sources); The Polish Foundation for Energy Efficiency (FEWE) proposed development of project aimed in transformation of market of electric motors and motor systems. The proposal was approved by Global Environment Facility GEF and beginning of 1999 development of the full scale programme has started. The FEWE obtained support from Polish National Energy Conservation Agency - KAPE, Polish Copper Promotion Center – PCPM and United Nations Development Programme – UNDP.

3 The PEMP

The development of full scale project started with identification of existing barriers then the mechanisms for overcoming these barriers were developed.

3.1 Barriers to Energy Efficiency in Electric Motor Systems

A range of barriers has prevented Poland from realizing the economic potential for energy efficiency in electric motor systems. The project team conducted a survey of manufacturers and end-users, which resulted in the following ranking of barriers.

Financing

The respondents regard the financing barriers as very important. The most important barriers within the group are the following:

- lack of company’s financial means,
- lack of business partners/companies willing to take the risk and to finance the enterprise or too high prices of such services,
- difficult acquiring financial means from outside,
- low profitability of the investment in comparison with the risk involved,
- legal or fiscal obstacles.

Information

Lack of information was the second important barrier:

- insufficient information on possibilities of external co-financing of the investments,
- insufficient information about energy services companies,
lack of information about verified examples of the effective use of the projects (demonstration projects),
lack of well-known standard methods of economical effectiveness estimation of the investments,
lack of the profitability estimation of drives exchange for energy-efficient ones,
insufficient information on available technologies and devices,
lack of or insufficient knowledge about any possibilities of the electric drives energy cost reduction in a company.

Low priority
The low priority of energy efficiency is also an important barrier. The electric energy costs as a part of the production and services costs are in Poland 2-10 per cent (on the average 4 per cent) of the overall costs.
lack of or inefficient programmes of the production and services cost reduction in a company,
restructuring the company (products, market position, new technologies, etc.) has a much higher priority,
low share of the energy cost in the production or services costs, and their insignificant role within the general company’s strategy and the company’s actions,
lack of either organizational or technological skills on how to manage the costs and to make the investment decisions.

Market
Among market barriers (ranked as 3 in the 0-6 scale) the most important are the following ones:
offer concerning this particular area from financial services providers (no such specialised financial service providers),
offer for the technical and financial risk estimation as well as for the insurance from such risk,
offer of the ESCO type: from a recognition to the investment realisation in a form of self-financing from costs’ savings,
offer from energy processing companies, including energy suppliers,
offer from producers of the devices.
The survey showed also that a large majority of users/investors (approximately 75%) was prepared to invest in energy efficient motor systems if the simple payback period for the investment were less than 2 to 3 years (see Table 1).
Table 1: Willingness to invest in energy efficient motor systems

<table>
<thead>
<tr>
<th>Simple Payback Period (PBP)</th>
<th>Share of the respondents</th>
</tr>
</thead>
<tbody>
<tr>
<td>less than 1 year</td>
<td>95 %</td>
</tr>
<tr>
<td>less than 3 years</td>
<td>63 %</td>
</tr>
<tr>
<td>less than 6 years</td>
<td>6 %</td>
</tr>
<tr>
<td>less than 10 years</td>
<td>3 %</td>
</tr>
</tbody>
</table>

Based on the above information, the project team identified two general categories of barriers:

1. Barriers to profitable investments. The economic potential of investments with a PBP of less than 2 to 3 years, which is the criterion applied by most investors, is not currently exploited. Nonetheless, there are a number of projects that have been identified with low pay back periods. For example, in district heating and water utility projects involving the replacement of standard motors with energy efficient motors, pay back periods of between 2.2 and 2.8 years were possible with expected savings of between 520 and 566 MWh/year. However, the current market share of high efficient electric motors that would capture these savings is practically zero.

2. Barriers to investments with lower profitability. An even greater potential exists for investments with a PBP of up to 6 years. However, these projects are not implemented because profitability is perceived as too low by potential investors.

PEMP address both barriers to profitable investments and barriers to investments with a lower profitability. The preliminary phase of the project assessed these barriers by focusing on sectors with the highest expectancy of full-scale implementation (i.e., in water, heat, electric energy, gas supply sectors, and in industry, mainly the chemical industry). The barriers were found to be the same across these specific sectors.

3.2 Scope of the program

The PEMP is a five years programme financed by Global Environment Facility which consists of four main activities.

1. The first major activity focuses on building capacity and raising awareness by providing information and services related to energy efficient electric motor systems. This will be delivered through the PEMP Centre at FEWE, which will be strengthened as a sustainable mechanism for the provision of information and services for the energy efficient electric motors market. The focus will be on generating and disseminating market information on energy efficient motors, providing technical and business advisory services for pilot projects and business project development, establishing and operating an advisory system for the energy efficient motors market, and supporting the development and implementation of industrial energy efficiency policy.
Table 2: Project objectives and corresponding activities, outcomes, and barriers addressed

<table>
<thead>
<tr>
<th>Objectives</th>
<th>Description of Activities</th>
<th>Outcomes</th>
<th>Barriers Addressed</th>
</tr>
</thead>
</table>
| (1) Build Capacity and Raise Awareness by Providing Information and Services Related to Energy Efficient Electric Motor Systems | • prepare a business plan for the PEMP Centre  
• generate and disseminate market information on energy efficient motors  
• provide technical and business advisory services for pilot projects and business project development  
• establish and operate an advisory system for the energy efficient motors market  
• support the development and implementation of industrial energy efficiency policy | • establishment of a sustainable mechanism for the provision of information and services for the energy efficient electric motors market  
• availability of information on the energy efficient motors market in Poland, thereby establishing a market baseline and providing a resource on market activities  
• easily-accessible information on the benefits of energy efficient motors  
• availability of technical and business advisory services for pilot projects and business project development  
• trained project developers, industry, and financial institutions on energy audits, feasibility studies, funding applications, etc. | • lack of awareness and information  
• lack of financing mechanism and sources  
• lack of project development capacity  
• lack of focused energy efficiency policy  
• lack of strong interest groups/advocacy of energy efficient motor systems  
• no consideration of additional benefits of energy efficient motor systems in business and financial decision-making |
| (2) Demonstrate Efficient Motors under Polish Market Conditions | • implement demonstration projects for energy efficient motor systems in 4 key sectors  
• disseminate information gained through the demonstration projects | • awareness of efficient options increased  
• cost-effectiveness and technical benefits of investments proven | • lack of awareness and information  
• high incremental investment costs for energy efficient motor systems  
• no consideration of additional benefits |
| (3) Stimulate Market Development and Competition Using a Financial Incentive Mechanism | • establish financial incentive programme for efficient motor manufacturers  
• develop and launch an advertising campaign to create demand  
• provide a competitive pre-allocation to successful applicants  
• increase awareness through labeling of energy efficient motors  
• conduct outreach to customers to enhance awareness and acceptance of energy efficient motors  
• performance allocation | • cost-effectiveness of investments in efficient motors increased  
• increase in sales and open the market for efficient motors  
• increase in awareness | • lack of financing mechanism and sources  
• high incremental investment costs for energy efficient motor systems  
• lack of awareness |
| (4) Develop and support energy efficiency policy in industry for energy efficient drives | • increase knowledge of industrial energy efficiency policy among decision-makers  
• develop a national policy for industrial energy efficiency  
• develop schemes for the labeling, Long Term Agreements (LTA) and Best Practice Initiatives (BPI)  
• link and co-ordinate with other energy efficiency programmes | • improvements in the Polish policy  
• dedicated involvement of policy makers | • lack of a policy framework  
• lack of policy instruments  
• low priority of energy efficiency |

(2) The second major activity involves demonstration projects to establish and showcase the technical and economic benefits of energy efficient motor systems, and increase awareness.
(3) The third major activity has the objective of stimulating market transformation and competition through a financial incentive mechanism, supported by coordinated and targeted awareness raising activities.

(4) The fourth, a policy component, comprises both institutional and information instruments, and has been identified as a separate component because it addresses a different target group than the other components and requires a different approach on a national government level.

Table 2 summarizes the major project activities and related tasks, their objectives, and the barriers they address.

### 3.3 Expected results

The main objective of the project is to reduce domestic GHG emissions in Poland by overcoming existing barriers for increased market penetration of energy efficient motors and related efficiency improvements in the electric motor system (including variable speed drives), particularly, but not exclusively, in the manufacturing industry, the energy sector (heating), the utility sector (water supply and sewage treatment) and mining.

The project has established the following specific targets:

- Increase energy efficient motor sales in Poland to app. 15% of the total motor market as a direct result of PEMP during the duration of the programme (five years);
- Increase the efficiency of electric motor systems by increasing the penetration of variable speed drives in combination with energy efficient motors;
- Achieve a medium-term increase of energy efficient motors sales of 30% of the total motor market in the year 2013;
- Save electricity by promoting the optimization of electric motor systems, including the implementation of energy efficient motors and variable speed drives to a level of 55.7 GWh/year in 2007 and 231.6 GWh/year in 2013; and,
- Reduce domestic GHG emissions by 832 kton CO2 by the end of the year 2008 (directly attributable to PEMP and cumulative over the project lifetime), and 3.7 Mton CO2 by 2013, including the medium-term impact (cumulative over the lifetime of the investments).

### 3.4 Project implementation phase

After several years of development process, the Polish Energy Efficient Motors Programme has started in the year 2004. The PEMP Center was set up and preparations for first demonstrations and rebate sale of energy efficient motor have started. However problems occurred after accession of Poland to the European Union on May 01 2004. It is required by the European Union regulations that public help for the particular company, which exceeds 100 000 Euro in 3 successive years, should be notified to the
European Commission for permission. This could apply in case of Objective 2 (Demonstrations projects) and Objective 3 (Stimulate Market Transformation Using Financial Incentive Mechanism for Energy Efficient Motor Manufacturers) of the PEMP project. The Polish Office for Competition and Consumer Protection, which became a link to the European Commission in this area have been asked for acceptance. Both, Objective 2 as well as Objective 3 of the PEMP project could not be commenced before acceptance for public help was received.

It is also worth to mention other source of difficulties – lack of commonly recognized European standard for determining losses and efficiency of high efficient electric motor. Existing standard EN 60034-2 seems to be not enough precise for the purpose of fund allocation for rebate sale and for prediction of energy savings, other standards suitable for these purposes i.e. Polish standard PN-E-06741 or new international standard IEC 61972 are not commonly accepted by manufacturers.

References

Project Document - Polish Energy Efficient Motors Programme (PEMP) POL/02/G31/A/1G/99 (PIMS 1645).
Policies and International Issues II
Creating a Standards Framework for Sustainable Industrial Energy Efficiency

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Abstract

Industrial motor-driven systems consume more than 70% of global manufacturing electricity annually and offer one of the largest opportunities for energy savings. Program experiences in the US, the United Kingdom, and China have demonstrated that energy savings opportunities are typically 20% or more for these systems across all industrial sectors.

Despite the potential benefits, energy savings from motor-driven systems have remained largely unrealized worldwide. Both markets and policy makers tend to focus on system components, which have a typical improvement potential of 2-5% versus 20-50% for systems. Determining how to optimize a system requires a high level of technical skill. In addition, once an energy efficiency project is completed, the energy savings are often not sustained due to changes in personnel and production processes. Although training and educational programs to promote system optimization have proven effective, these resource-intensive efforts have only reached a small portion of the market.

The same factors that make it so challenging to achieve and sustain energy efficiency in motor-driven systems (complexity, frequent changes) apply to the production processes that they support. Yet production processes typically operate within a narrow band of acceptable performance. These processes are frequently incorporated into ISO 9000/14000 quality and environmental management systems, which require regular, independent audits to maintain ISO certification, an attractive value for international trade.

This paper presents a new approach to achieving industrial system efficiency (motors and steam) by creating a top-down and bottom-up framework that will encourage plants to incorporate system energy efficiency into their existing ISO management systems. We will describe the Industrial Systems Framework, which is being prepared for China, but applicable elsewhere, that includes national standards and an Industrial Systems Optimization Library. ISO work instructions are part of the framework, so that a plant can easily incorporate projects into their ISO Quality Environmental Manual. The goal is to provide a plant-based mechanism that helps each company maintain their focus on energy efficiency commitments, provide visibility for its achievements, and provide verification of results for financial backers (including carbon traders) to help stimulate much greater industrial energy efficiency.

1 Introduction

Industrial motor-driven systems consume more than 70% of global manufacturing electricity annually and offer one of the largest opportunities for energy savings. The energy savings potential from motor-driven systems (as well as other industrial systems, such as steam) remains largely unrealized worldwide. Both markets and policy makers tend to focus on individual system components, which have a typical improvement potential of 2-5% versus 20-50% for complete systems, as documented by program experiences in the U.S., U.K., and China.

1 2194 billion kWh annually based on analysis conducted by Lawrence Berkeley National Laboratory, Alliance to Save Energy, and Energetics July 2004
2 US-Motor Challenge, BestPractices; UK- Best Practice Programme, Motor Challenge; China Motor System Energy Conservation Program
Several factors contribute to this situation, including the complexity of these systems and the institutional structures within which they operate. Industrial motor-driven systems are ubiquitous in the manufacturing environment, but their applications are highly varied. System optimization cannot be achieved through component standards or labeling or “one size fits all” approaches. The presence of energy-efficient components, while important, provides no assurance that a motor-driven system will be energy-efficient. In fact, the misapplication of energy-efficient equipment in industrial motor systems is common. The disappointing results from these misapplications can provide a serious disincentive for any subsequent effort toward system optimization.

System optimization requires taking a step back to determine what work (process temperature maintained, production task performed, etc) needs to be performed. Only when these objectives have been identified can analysis be conducted to determine how best to achieve them in the most energy-efficient and cost-effective manner.

The skills require to optimize systems are readily transferable to any individual with existing knowledge of basic engineering principles and industrial operations. Training and educational programs in the US and the UK have successfully transferred system optimization skills since the early-1990s. A recent United Nations Industrial Development Organization (UNIDO) pilot program in China demonstrated that a concentrated training program could successfully transfer these skills across language and cultural barriers (Peters and Nadel). Although effective, training to adequately prepare an individual to conduct system optimization assessments is resource-intensive and best suited to developing a small cadre of skilled professionals to work with plant personnel.

Once the importance of optimizing a system and identify system optimization projects is understood, plant engineering and operations staff frequently experience difficulty in achieving management support. The reasons for this are many, but central among them are two: 1) a management focus on production as the core activity, not energy efficiency and 2) the existence of a budgetary disconnect in industrial facility management between capital projects (incl. equipment purchases) and operating expenses. As a further complication, experience has shown that most optimized systems lose their initial efficiency gains over time due to personnel and production changes. Since system optimization knowledge typically resides with an individual who has received training, detailed operating instructions are not integrated with quality control and production management systems.

One of the most tested mechanisms used to promote energy efficiency and market transformation requires the application of energy efficiency standards. However, this paper proposes system standards, not equipment component standards. Moreover, the system that we are describing extends beyond the motor-driven system to the management system, and builds industrial energy efficiency from both a top-down and a bottom-up approach.

Since production is the core function of most industrial facilities, it follows that the most sophisticated management strategies would be applied to these highly complex processes. Successful production processes are consistent, adaptable, resource efficient,
and continually improving—the very qualities that would support industrial system optimization. Because production processes have the attention of upper management, the budgetary disconnect between capital and operating budgets is less evident. Unfortunately, efficient use of energy is typically not addressed in these management systems in the same way as other resources such as labor and materials. We feel that the answer lies in fully integrating energy efficiency into these existing management systems.

A number of management systems are currently used by industrial facilities across most sectors to maintain and improve production quality. We have selected ISO as the management system of choice for further study because it has been widely adopted in many countries, is used internationally as a trade facilitation mechanism, is already accepted as a principal source for standards related to the performance of energy-consuming industrial equipment, and has a well-established system of independent auditors to assure compliance and maintain certification. For the purpose of this discussion, ISO includes both the quality management program (ISO 9001:2000) and the environmental management program (ISO 14001), which can share a single auditing system.

This paper proposes a link between ISO 9000/14000 quality and environmental management systems and industrial system optimization that is based on the creation of a framework. This industrial standards framework includes energy efficiency standards, policies, training, and tools that have the net effect of making system optimization for energy efficiency as much a part of typical industrial operating practices as waste reduction and inventory management. The objective is a permanent change in corporate culture using the structure, language, and accountability of the existing ISO management structure. This is market transformation primarily from the inside out. A proposed standards framework for China will be presented in detail, but most elements of this approach would be equally applicable in other industrialized or industrializing countries.

2 Background

2.1 ISO Quality and Environmental Management Systems

The operation of industrial motor systems can have a significant environmental impact on an organization. Inefficient systems not only use up to twice the energy required of optimized systems, but are also responsible for off-quality products, waste and scrap. Organizations do not normally recognize this impact. The rework of off-quality products resulting from improperly operating systems can double the energy input of a product and produce additional waste. Products that cannot be reworked result in increases in the amount of scrap requiring disposal. Properly operating systems not only have reduced energy input requirements, but in many cases, reduce other energy inputs in the tools and equipment being operated by the system.

Most energy audits of such systems result in recommendations that apply to the current factory production levels. In cases where future expansion is anticipated at the
time of the audit, the expansion is commonly included in the recommendations. After the recommendations have been implemented and the auditor is gone, there is no procedure in place to ensure continued proper operation of the system. Often, improvements in motor systems are made but changes to production levels and/or personnel negate the improvements over time. In other cases, operating personnel simply go back to doing things the way they were doing them, again negating the improvements.

In order to ensure persistence for energy efficiency savings from system optimization projects, a method of verifying the on-going energy savings under a variety of operating conditions must be developed. This method must ensure that changes that could affect the operating characteristics of the motor system are analyzed in light of the new operating paradigm for that system. A vehicle exists for continuously monitoring an organization’s adherence to the new motor system operating paradigm. That vehicle is the ISO 9000/14000 Series Standards.

The purpose of ISO 14001 is to provide a framework for organizations to achieve and demonstrate their commitment to an environmental management system that minimizes the impact of their activities on the environment (a similar framework for ISO 9001:2000 pertains to quality). The framework does not include any specific requirements, only a means of achieving goals set by the organization. This ISO standard also provides for an audit procedure to verify that established policies of the organization are being followed. To maintain certification, participating companies must maintain a Quality Environmental Management (QEM) Manual.

The environmental management system model for this standard is composed of six elements:
1. The establishment of an environmental policy by the organization
2. Planning
3. Implementation and operation
4. Checking and corrective action
5. Management review
6. Continual improvement

Once top management has defined the organization’s environmental policy, the next step is planning. In the ISO 14001-1996 Environmental management systems – Specification with guidance for use, Section 4.3.1 states:

The organization shall establish and maintain (a) procedure(s) to identify the environmental aspects of its activities, products or services that it can control and over which it can be expected to have an influence, in order to determine those which have or can have significant impacts on the environment. The organization shall ensure that the aspects related to these significant impacts are considered in setting its environmental objectives.

There are two approaches to establishing and maintaining efficient operation of motor systems. Both approaches involve the “Planning” phase and the “Implementation and operation” phase of ISO 14001. For operations that are ISO 9000 certified, but not ISO 14000, these same steps can be incorporated into the ISO 9000 Quality Standards.
First, a set of best practices standards can be developed in the ISO format that can be incorporated in the “Planning” portion of ISO 14001. From those standards, work instructions can be written for the “Implementation and operation” portion. By making these “best practices” standards part of ISO certification, an organization ensures that these best practices will become part of the organization culture through the continuing audit procedure required by ISO. By making these best practices ISO-friendly, organizations can easily incorporate them into existing ISO systems. The number of standards incorporated can be determined by the individual organization. As more goals are reached, new standards can be included, further improving the energy efficiency of the motor systems’ operation and making efficiency part of the culture. Second, for organizations that are involved in carbon financing, ISO standards can be developed that are specific to that organization’s on-going commitment to energy efficiency and pollution reduction. These standards can be developed by the entity conducting the energy efficiency audit on a motor system, or they can be copied from the System Optimization Library and modified to fit individual requirements.

2.2 A Brief Primer on ISO Terminology

As described in this paper, a procedure refers to a general description of a process and is incorporated into a company’s QEM Manual.

The first step is for a company to develop a policy of efficient operation of motor-driven systems within their facility, then develop and implement system procedures that are consistent with that policy:

- The company must develop procedures for motor-driven systems;
- The company must document those procedures and keep the documentation up to date;
- Each procedure should specify its purpose and intended scope, and
- Procedures may also refer to detailed work instructions that explain exactly how the work should be performed.

A project refers to a specific activity designed to contribute to meeting the ISO requirement for continuous improvement. Examples of projects include: initiating a leak management program or replacing a throttle valve on a pumping system with a speed control device. Work instructions are step-by-step information (text, diagrams, photos, specifications, etc) to assist operations staff in maintaining the improvements realized through implementation of a project. Examples include: instructions on how and when to check leaks and repair them or maintenance information to ensure that the pump system speed control device continues to function efficiently. Work instructions are typically posted for or easily accessible to operations staff.

The next section presents the basic elements of an industrial standards framework, followed by a model for implementation of the framework in China that links it to ISO quality and environmental management programs.
3 Elements of an Industrial Standards Framework

The basic elements of an industrial standards framework include energy efficiency standards, policies, training, and tools. The purpose of the framework is to standardize, measure, and recognize industrial system optimization efforts. The framework builds on existing knowledge of “best practices” using commercially available technologies and well-tested engineering principles. The framework seeks to engineer industrial systems for reliability and productivity, as well as energy efficiency. Factories can use the framework to approach system optimization incrementally in a way that maximizes positive results and minimizes risk and downtime. Table 1 provides a listing of these elements, their purpose, and relative importance in the overall scheme.

A key element of the framework is a corporate energy management program. Since ISO currently has no explicit program for energy efficiency, the framework builds energy efficiency into an ISO continuous improvement program (9001:2000 or 14001) through an ISO-compatible energy management program. The corporate energy management program that seems to offer the most straightforward, publicly accessible, ISO-friendly approach is the American National Standards Institute Management System for Energy (ANSI/MSE 2000) developed by Georgia Institute of Technology. This standard is also compatible with Energy Star Guidelines for Energy Management. ANSI/MSE 2000 was developed by individuals with experience with ISO certification and is quite suited for future consideration as an ISO standard. Formal integration of energy efficiency into the ISO program certification structure (most likely as part of the ISO 14000 series), while desirable for the explicit recognition of energy efficiency as an integral part of continuous improvement, would be a resource- and time-intensive undertaking. Since the current ISO program structure creates no specific barriers to the inclusion of energy efficiency projects, immediate program integration is not a high priority. Instead, the Industrial Standards Framework recommends the use and further testing of ANSI/MSE 2000 in multiple countries with the long-term goal of seeking ISO recognition.

The Chinese government has expressed interest in adapting ANSI/MSE 2000 as a standard for China and has had it translated for further study.

3.1 Industrial Systems Optimization Library

The Industrial Systems Optimization Library (Library) is a series of Word documents organized via an extensive table of contents and guidelines. To effectively use the Library, the user needs to be familiar with the system optimization approach (awareness level training) but does not need to become a system optimization expert. Training on use of the Library requires a much smaller time investment than that required for a systems optimization expert. This approach is designed to the “80/20” rule for achieving persistent energy savings in systems of moderate complexity. For highly complex systems, or for those who seek to achieve full optimization, the assistance of a highly trained system optimization expert is recommended.
**Table 1: Elements of an Industrial Standard Framework**

<table>
<thead>
<tr>
<th>Element</th>
<th>Category</th>
<th>Purpose</th>
<th>Current Status</th>
<th>Importance</th>
<th>Compatibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corporate Energy Management Standard</td>
<td>Standard-Voluntary or Mandatory</td>
<td>Provides organizational guidance for “hardwiring” energy management into company management practices.</td>
<td>ANSI/MSE 2000 (US); adaptation planned for China (adaptation planned for China)</td>
<td>Essential for management support; compliance w/standard can be met through other elements</td>
<td>Written as possible ISO standard w/ ISO-friendly documentation and continuous improvement requirements</td>
</tr>
<tr>
<td>Training</td>
<td></td>
<td>Prepares management to implement standard</td>
<td>Existing training through Georgia Tech (US)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Motor System Standards</td>
<td>Standard-Voluntary or Mandatory</td>
<td>Sets efficiency goals for motor systems enforceable through periodic measurement &amp; application of best practices</td>
<td>Standards GB/T 13466 &amp; GB/T 12497 (China). Note: China also has a mandatory Motor Efficiency Standard GB 19861-2002</td>
<td>Very helpful, broadly establishes system efficiency goals</td>
<td>References Energy Management Standard; designed to be used with Library</td>
</tr>
<tr>
<td>Training</td>
<td></td>
<td>Prepares factories to comply w/standard</td>
<td>Training to be developed through CNIS (China)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>System Optimization Library</td>
<td>Tool-Electronic reference document</td>
<td>Provides factory personnel and experts w/guidance on system optimization within the ISO context of procedures, projects, &amp; work instructions</td>
<td>Library samples developed &amp; reviewed; demonstration project planned (China)</td>
<td>Essential—provides an incremental path to continuously improve and maintain system efficiency</td>
<td>Written in ISO language for use in ISO 9000 or 14000 program; supports corporate energy management goals</td>
</tr>
<tr>
<td>Training</td>
<td></td>
<td>Prepares factory personnel and system optimization experts to use Library (follows system optimization awareness training)</td>
<td>Training to be developed as part of demonstration project (China)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>System Optimization Training</td>
<td>Training</td>
<td>Expert training prepares a cadre of engineers to conduct factory assessments, train factory personnel, &amp; assist in project development</td>
<td>Expert &amp; awareness training developed as part of UNIDO Motor System Program (China)</td>
<td>Essential—provides the technical skills for small group of experts and prepares them to train others</td>
<td>Consistent with the approach used for Motor System Standard, System Optimization Library</td>
</tr>
<tr>
<td>ISO 9001:2000 and/or 14001 certification</td>
<td>Independent Certification</td>
<td>Determines whether a factory is meeting ISO objectives for continuous improvement via procedures, projects, &amp; work instructions</td>
<td>Global program with &gt;500,000 participating companies</td>
<td>Essential for sustaining &amp; improving energy efficiency</td>
<td>Other elements provide path for maintaining certification</td>
</tr>
<tr>
<td>Energy efficiency targets by industrial sector</td>
<td>Policy</td>
<td>Provides plant-specific energy efficiency targets based on continuous improvement that is non-prescriptive and developed in cooperation with the industrial sector</td>
<td>Pilot program developed and demonstrated in Chinese steel industry; based on European experience</td>
<td>Very helpful—engages management in efficiency objectives, leading to other elements</td>
<td>Compatible with all elements</td>
</tr>
<tr>
<td>Government Recognition of Outstanding Energy Management</td>
<td>Policy</td>
<td>Provides meaningful recognition program for factories who initiate and sustain continuous improvement for energy efficiency</td>
<td>Proposed for China</td>
<td>Very helpful for motivating companies to become energy efficient</td>
<td>Recognition based on measurable results from other elements</td>
</tr>
</tbody>
</table>
The Library provides the user with guidance concerning how to approach implementation of an energy efficiency project once an opportunity has been recognized. It is designed to support an incremental approach to optimization, by providing a logical sequence of energy efficiency projects that build on each other until the targeted performance is obtained. A company can decide how quickly to proceed with optimization and on which systems. The most critical element of the Library is the work instructions, which provide written documentation that “hardwires” a new project or procedure into standard management practices. Once a set of work instructions has been integrated, operational deviations from these instructions (such as to returning to former inefficient practices) are a path of most, rather than least, resistance. If the company is ISO certified, deviations from work instructions without a well-documented and supported reason attract negative attention and management notice.

The proposed Library will require about eighteen months to develop and an equal time period to test it in industrial facilities. A demonstration project is proposed for Shanghai and Jiangsu, which have a large number of ISO facilities and trained system optimization experts.

4 Establishing an Industrial Standards Framework in China

Industrial motor systems are a major user of electricity in China, accounting for more than 50% of overall electricity use. Optimizing half of these motor systems would achieve a 20% average energy savings (a reasonable long-term goal). This would save the equivalent of more than US$4 billion annually and reduce carbon emissions by more than 25 MMT annually.

Through a combination of standards, tools, and training, the Industrial Standards Framework seeks to make energy efficiency an integral part of corporate management systems, with a special emphasis on ISO as the principal international management system. ISO certification has now become a significant trade facilitation vehicle for developing countries—for example; China leads the world in growth in the number of new certifications with approximately 100,000 certificates issued through December 2003 (ISO Survey 2004).

The proposed Industrial Standards Framework in China would build on both the skills developed in Jiangsu and Shanghai through the UNIDO pilot program (Williams, et al 2005), government interest and support for energy efficiency standards and industrial energy efficiency in general, and the prevalence of ISO-certified plants in China.
4.1 The Role of Government

The primary role of government in the Framework is to develop and issue energy efficiency standards and to support the provision to industry, consultants, and suppliers of training and tools to aid in compliance. A further role is to recognize outstanding efforts that exceed compliance requirements.

Standards for corporate energy management provide a framework for companies to integrate an energy efficiency ethic into their management practices. Government-sponsored training prepares plant engineers and emerging energy service companies with:

- The skills to recognize energy efficiency opportunities via training on system optimization techniques;
- An understanding of standards requirements;
- Knowledge and access to the System Optimization Library for use in developing and implementing projects; and
- Government-sponsored recognition based on verified energy savings provides industrial plants with the incentive to document and report project savings.
4.2 The Role of System Optimization Experts

Engineers (plant-based and consulting) are trained following the model developed in the UNIDO China Motors Program by a team of international experts and the most skilled practitioners from the first group of experts trained through the UNIDO program. This group of experts will be expected to: provide awareness training to encourage plants to undertake system optimization improvements; conduct plant assessments to identify system optimization opportunities; work with plants to finance and develop projects based on these findings; and prepare case studies of successful projects. This cadre of experts will also form the nucleus for future training of additional experts.

4.3 The Role of Industrial Plants

Industrial plants are responsible for compliance with national standards for corporate energy management, which typically require:

- an energy management team led by an energy coordinator with strong management support;
- policies and procedures to promote energy efficiency;
- projects to demonstrate continuous improvement in energy efficiency; and
- monitoring and measurement to document achievement of annual energy efficiency goals.

These requirements can be achieved through: the application of system optimization techniques (with their own staff or outside experts) to identify energy efficiency opportunities; and use of the System Optimization Library to develop and document projects and work instructions in ISO-compatible (also MSE 2000-compatible) language.

If the industrial plant is ISO-certified, the System Optimization Library can be used as a resource to incorporate includes new work instructions, projects and procedures into their current ISO 9000/14000 program. The periodic ISO audit provides independent verification of compliance with written procedures and policies and energy-efficient operation becomes part of the factory culture.

5 Conclusion

Industrial motor system optimization offers great potential for energy savings that is largely unrealized. Training alone, while essential for creating the awareness and skills required to identify potential projects, is insufficient to ensure the persistence of energy savings once these projects are implemented. What is needed is a framework that introduces a standardized approach to system optimization that includes measurement, documentation, and ongoing work instructions. The existing ISO quality and environmental management programs provide an effective foundation for this framework that is international in scope, relevant to both industrialized and industrializing countries, and already incorporates documentation, continuous improvement, and independent verification requirements. Since these programs are already part of the "language of
management” and are widely accepted, the inclusion of system optimization practices becomes just one more aspect of an ongoing effort, rather than something new and resource-intensive to implement.

A framework that employs training, implementation of standards for efficient operation of energy systems, and integration of system optimization practices into a company’s existing operating paradigm will result in sustainable energy efficiency. A program based on this framework can be delivered in selected countries where energy and fuel prices demand attention to energy efficiency and where governments are supportive of using standards to upgrade environmental and energy management practices. China offers particularly fertile ground to demonstrate these concepts, because of its support for energy efficiency standards, problems with adequate electrical supply, and large number (100,000) of ISO-certified industrial facilities.

Following demonstration of the successful application of energy efficiency standards in China and several other countries, national standards authorities from these countries may wish to approach ISO with a view to integration of energy systems optimization into international standards regimes.

6 References


Energy Efficiency of Industry and Trade

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Abstract nationwide campaign: energy efficient systems in industry and trade

Numerous studies have shown that measures to improve energy efficiency of industrial motor driven systems are insufficiently implemented by industrial enterprises - in spite of their huge technical and economic saving potential.

In Germany a nationwide campaign was set up in order to decisively open up the market for energy efficient techniques. The campaign was developed by Deutsche Energie-Agentur GmbH (dena – the German Energy Agency is a competence centre for energy efficiency and renewable energies) together with the sectors “pumps + systems” and “compressors, compressed air and vacuum technology” of Verband Deutscher Maschinen- und Anlagenbau (VDMA – the German Engineering Federation is a network of around 3,000 engineering industry companies in Europe). It is supported by the Bundesministerium für Wirtschaft und Arbeit (BMWA – the Federal Ministry of Economics and Labour) and is carried out together with partners as private institutions and industrial enterprises. Project financing is organized as a public private partnership.

The advisory campaign comprises:

- Target group oriented public relation, to point up, that measures to improve energy efficiency are worthwhile in different ways and to motivate end-user to keep the whole system in their mind;
- Providing technical dimensioning tools, technical and particularly commercial information, life cycle cost analysis tools, etc;
- Executive consultancy addressing technical and commercial staff, as well as upper management in industrial enterprises, in order to motivate decision makers not only to consider the reduction of energy consumption but also to start realizing measures. Advice on concomitant opportunities of financing measures is given.

The campaign focuses on electrical driven systems as described in the European “Motor challenge programme”. The market for energy efficient techniques and technologies (motor driven pump-, ventilation- and compressed air systems) is stimulated. The concerted initiative, which concentrates on decision makers, aims to address a majority of small and medium-sized enterprises in Germany.

To receive information, interested customer can contact the project management, carried out by the German Energy Agency, or use the website www.system-energieeffizienz.de.

1 Introduction – Energy saving potentials in industrial enterprises

Numerous studies document substantial economic cost- and energy-saving potentials, which can be harvested by process-optimization during planning, installation and operation of electrical driven applications. Apart from the use of energy-efficient technical components, like high-efficient electrical motors or frequency converters, an integrated view of the overall system, which causes substantial cost savings, could also increase energy efficiency.

Today’s final electricity consumption of all existing electrical driven applications in industry could be reduced by suitable optimization measures and investments with almost 20%. That means, within the European Union (EU 15) about 181 TWh could be
saved per year. Only related to pump systems the energy-saving potential is approximately 46 TWh. On the assumption of an electricity tariff of 8 eurocent/kWh a cost-saving potential of annually 3.7 billion euro results.

Figure 1: Electrical energy consumption and reduction potential in EU 15 (percentage of industrial consumption, in 2000)

The disclosure of existing saving potentials and the implementation of energy-efficiency-measures are determined by the national framework (laws, regulations, support measures), the basic economic conditions of the enterprises (tariffs for electricity consumption, capital availability etc.) and the operational conditions. Cost-efficiency of optimized systems usually translates in terms of reduced operating- and electricity-costs during the period of operation. Often financing offers and services are necessary for the implementation of energy saving measures, apart from an increase in the technical planning know-how. If these financing offers are missing, expedient measures are not realized, despite of recognized chances.

In addition there are a number of obstacles in enterprises, which restrict the use of existing potentials.

**Technical obstacles:**

For instance the complexity of combined systems could lead to operational staff not being able to appraise effects of optimization measures in other places. Furthermore, due to missing measuring-instruments allocation problems exist concerning the correla-
tion of consumption to consumption generating aggregates. Energy efficiency has often a minor importance compared to service and availability.

**Economic obstacles:**

In enterprises the energy costs are mostly underestimated in comparison to total manufacturing costs. Moreover, lack of capital or validating investment measures only by means of the payback period and not on basis of return on investment, could be the crucial factor for enterprises not to realize possible measures.

**Organizational obstacles:**

Distributed or unclear competencies, as well as lack of time of responsible persons, are common reasons for not recognizing and using energy-saving potentials. In addition, internal cost calculation systems, which cannot make an allocation of the costs to the cost causers, cannot assign benefits to the relevant initiators. There is numerous information about pump systems and energy efficiency, but in enterprises exists a lack of information about energy costs as well as about system know-how considering energy consumption.

The obstacles mentioned above can be diminished by a holistic view and analysis of the energy using systems, by optimization of the organizational structures and by the dismantling of information deficits. Therefore campaigns, which remedy the mentioned obstacles and convince industrial management to act for the company’s benefit, can make a contribution to the awareness of energy efficiency potentials and can be motivating for the realization of reasonable measures.

2 **Campaign "Energy Efficient Systems in Industry and Trade"

In 2004 the Deutsche Energie-Agentur GmbH (dena - the German Energy Agency for energy efficiency and renewable energies) together with the sections "pumps + systems" and "compressors, compressed air and vacuum technology" of Verband Deutscher Maschinen- und Anlagenbau initiated a nationwide information and motivation campaign in order to decisively open up the market for energy efficient techniques by integrating information and existing assistance tools. The campaign "Energy Efficient Systems in Industry and Trade" addresses itself to enterprises in all industrial sectors, with focus on small and medium-sized enterprises.

The campaign is accompanied by a professional marketing strategy connecting various ways of promoting and communicating the advantages of energy efficient systems in industry and trade. Financing is organized as a public private partnership in equal parts of public and private means. This project is supported by the Federal Ministry of Economics and Labour (BMWA) in Germany. At the beginning of the campaign pump systems will be in the focus of the activities. In the course of the campaign-process further systems as fans and compressors and their drives will be addressed. The campaign is
planned up to the end of 2007. It will be linked to the European Motor Challenge Programme, which has officially been launched in February 2003 by the European Commission. The Motor Challenge Programme aims at accelerating the improvements of motor driven systems (pumps, compressors, fans, drives) on a voluntary basis.

The objective of the campaign is not only to reveal huge saving potentials but also to motivate the decision makers in companies to exploit them. The competitiveness of enterprises can increase on basis of cost saving potentials. Beyond it this campaign generates positive market effects for energy-efficient technologies.

The campaign "Energy Efficient Systems in Industry and Trade" supplies adequate information and consulting offers to several target groups and it develops accompanying press and public relations. Furthermore, it aims to motivate decision makers in industry and trade to realize energy-efficient measures. Special attention of the campaign is given to address directly end-users. For users of motor driven systems (decision makers with economic responsibility, plant engineers and technicians) as well as for plant planners, different offers are developed and nationwide communicated.

Plant engineers can receive assistance for a detailed analysis of consisting systems. They will be supported during the implementation-process of measures which increase the energy efficiency afterwards. Thus, the importance of technical obstacles decreases.

Managers are informed about economic energy-saving potentials including financing services (e.g. performance contracting). Procedures for procurement which consider life-cycle-costs are suggested to the purchasing department. Thus, the importance of economical obstacles decreases.

Endorsing leading persons to reorganise internal structures is the intention of the advisory service. In addition, accountancy department is given support how cost accountings must be arranged to make the success of energy-efficiency measures evident. Thus, the importance of organizational obstacles decreases.

The components of the campaign are described in the following figure 2.
2.1 Consultancy

The realization of energy efficiency measures will be activated by the offer of a modular advisory service (see Figure 3). A number of about 100 initial consultancies are supplemented by a fixed number of detailed energy saving analyses, which consider the relevant technical and economic aspects due to the surveyed technical system. Enterprises, which received an energy saving analysis and have problems with implementing efficiency measures, can receive an implementation consultancy. It addresses technical and commercial decision makers and focuses on financing and official promotion possibilities for the proposed measures.
Figure 3: Consulting modules

The modules “initial consultancy”, “energy saving analysis” and “implementation consultancy” are catalytic activities of the campaign: these modules support end-users to implement energy saving measures. Furthermore the results will be communicated by press releases (public relation). Successful energy efficiency projects with high practical relevance (Best Practice) are communicated with priority in order to motivate other users to imitate arrangements and proceeding. The partners of this campaign distinguish themselves and develop new energy efficient systems. An accumulative process will take place.

2.2 Press and public relation products

The nationwide campaign is used to be introduced by comprehensive press and public relation products. The press and public relation products of this campaign comprise:

- press conferences to various occasions, e.g. “beginning of initial consultancy”, “energy saving analysis” and “implementation consultancy” and special supplies on the website
2.3 Information

The spreading of information is focused on the medium Internet. Additionally printed information tools (leaflets, brochures etc.) are offered to multipliers and end-users.

The website of the campaign is launched at www.system-energieeffizienz.de. It serves as a forum for information and exchange. The website is directed to manufacturers, suppliers, plant planners and users.

Following contents are transported by the website:

- information,
- events,
- examples for energy efficiency projects,
- offers for enterprises,
- progress and results of the campaign,
- technical and particularly commercial information.

The offers for end-users in enterprises comprise brief introductions as well as technical manuals or other detail information for all target groups in enterprises (decision makers with economic responsibility, plant engineers and technicians), plant planners etc. Technical dimensioning tools, life cycle cost analysis tools etc. are also provided to users. Interested visitors of the website have the possibility to ask questions and to exchange information in the expert forum.

The information gives a general view of possibilities, which increase energy efficiency based on a high quality standard and independent on any manufacturer’s products line. The life cycle cost concept has the greatest importance for all information tools. It supports to assess comprehensively plant specifically energy efficiency and focus the economic advantage of electrical driven applications in industry and trade.

Figure 4 shows several components, such as frequency converter, electric motor, gearbox, pump, valve and pipe system, which can be part of a pump system.

There are numerous possibilities to increase energy and cost efficiency as well by means of planning of pump systems as of optimizing of extant systems. The life cycle cost concept gives support to analyse the energy- and cost efficiency of pump systems. Life cycle costs are costs, which are caused during the lifespan of a system as a result of purchase, installation, running, maintenance and cleaning.
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Motor MEPS in Australia: Future Directions and Lessons

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Abstract

Since 1 October 2001, three phase electric motors from 0.73kW to <185kW manufactured in or imported into Australia must comply with mandatory Minimum Energy Performance (MEPS) requirements, which are set out in AS/NZS 1359.5-2004 and enforced under state efficiency laws.

A 2nd round of MEPS levels for electric motors were announced in 2003/4 and will be implemented from April 2006 following the Australia Government’s decision to match world’s best regulatory practice for this product, currently found in North America. The effect of this 2nd round of MEPS is that only EFF1 compliant or equivalent motors will be able to be imported into Australia from 2006, and the Australian market will be transformed as only 30% of models on the Australian market in 2004 will be able to be imported after 2006.

Australia’s experiences may assist other countries when introducing or increasing the stringency of MEPS, including consultation and support of internationally recognised testing methodologies and facilitation of industry compliance. The future directions for the Australian MEPS program are discussed.

1 Introduction and Background

Since 1 October 2001, three phase electric motors from 0.73kW to <185kW manufactured in or imported into Australia must comply with mandatory Minimum Energy Performance (MEPS) requirements. These requirements are set out in Australian Standard/New Zealand Standard 1359.5-2000 and enforced under efficiency laws. Australian State and Federal Governments first became interested in regulatory options for three phase electric motors in 1994 and consulted with industry and their representative bodies to establish an effective regulatory regime. In early 2001, Ministers responsible for energy efficiency regulation agreed with a consensus promoted by all stakeholder groups (government, manufacturers, suppliers and users groups) to come into effect not earlier than October that year.

Studies of the motor supply market suggest the market is not driving improvements in energy efficiency as quickly as Australian governments desire (Energetics et al. 1994). The motors market appears to be subject to both information failure – where users do not have access to accurate and consistent information about products or the full costs of owning and operating products – and to market failure – where the most cost-effective products and solutions are passed up because of distortions in the market.

A 2nd round of MEPS levels for electric motors were announced in 2003/4 and will be implemented from October 2006 following the Australia Government's decision to match world’s best regulatory practice for this product. This process involved setting MEPS at levels broadly comparable with the most demanding MEPS adopted by Australia’s trading partners at that time.
2 Test Methods and Scope

Australian Standard/New Zealand Standard AS/NZS1359.5-2004 specifies the MEPS requirements. The MEPS requirements are set out as minimum efficiency levels. The measurement methodology specified in AS 1359. 101 of the standard sets out methods for determining the rated output of the electric motor, thermal performance and other related performance tests (pull up torque, various short circuit tests etc.). This standard is based on and is equivalent to IEC60034.1. The efficiency of motors is measured under tests similar or equivalent to the two major internationally-accepted testing methods used world wide, as follows:

- **IEC60034.2.** The Australian Standard (AS1359.102.1) is based on and is equivalent to IEC60034.2. In Australia, this method is also known as Test Method B and sets out methods for determining the efficiency of an electric motor, primarily using the summation of losses for AC cage induction motors (it also covers other motor types and methods of determining efficiency). This standard assigns a value of “0.5% of the full load input to the machine” as the stray load loss at full load; and for other loads, the value is varied as the square of the line current.

- **ANSI/IEEE 112-1984 (Method B) and NEMA MG1-1987.** The Australian Standard (AS1359.102.3) is based on and is equivalent to US test procedures ANSI/IEEE 112-1984 (Method B) and NEMA MG1-1987. It is also equivalent to the recently published IEC motor test procedure IEC 61972 which was published in November 2002. In Australia, this method is also known as Test Method A and sets out methods for determining the efficiency of a three phase electric motor using the summation of losses method, and includes an improved measurement of additional load losses (also called stray losses). To achieve this measurement, an accurate mechanical output (torque and slip) must be measured at the shaft of the machine. The standard demands a relatively high standard of testing and accurate instrumentation. The result is that a machine with relatively low stray losses will stand out against one with relatively higher stray losses. This means that a manufacturer who has gone to the trouble of improving the stray losses of the motor gains some benefit in the measured efficiency. Generally, the efficiency as derived by this method will work out to be slightly lower than an efficiency value derived by the summation of losses which assumed the 0.5% for stray load loss. For this reason the MEPS standard has had to include two different tables of efficiency to accommodate both methods.

The MEPS does not apply to submersible motors, integral motor-gear systems, variable or multi-speed motors or those rated only for short duty cycles (IEC 60034-2 duty rating S2). It is recognized that it is neither economical nor sensible to regulate motors that service applications where only short or intermittent duties prevail.

AS/NZS1359.5-2004 also specifies minimum levels for motors claimed as "high efficiency" in the market place. This specification means that suppliers’ should no longer make advertising claims about their motor’s high efficiency unless it meets the more stringent level.
3 Australian Market Characteristics

The sale of three phase motors of the sizes up to 132kW increased at an average rate of around 7% per year from 2000 to 2004. In 2004 nearly 381,000 motors of up to 132kW size were imported into Australia at an estimated cost of AUD318M. Australia is a net importer of electric motors and from 2000 to 2005 the volume of electric motor exported as a percentage of net imports has varied from <1% in 2000 and to over 9.5% in 2002. Data from the Australian Bureau of Statistics (ABS 2005) shows the origin of these imports from over 150 different countries. China, Italy, Brazil and Germany have been the top source countries for motors imports. However, motor imports from Thailand have increased significantly during past 2 years. Table 1 shows the number of electric motors imported from top 10 source countries over past 5 years.

Table 1: Number of Electric Motors Imported from Top 10 Countries by Year (ABS 2005)

<table>
<thead>
<tr>
<th>Country</th>
<th>2000</th>
<th>2001</th>
<th>2002</th>
<th>2003</th>
<th>2004</th>
</tr>
</thead>
<tbody>
<tr>
<td>China</td>
<td>65,263</td>
<td>71,166</td>
<td>73,870</td>
<td>90,824</td>
<td>128,509</td>
</tr>
<tr>
<td>Italy</td>
<td>54,649</td>
<td>52,309</td>
<td>59,478</td>
<td>62,410</td>
<td>48,146</td>
</tr>
<tr>
<td>Brazil</td>
<td>23,543</td>
<td>22,068</td>
<td>30,072</td>
<td>33,823</td>
<td>31,829</td>
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<tr>
<td>Germany</td>
<td>30,639</td>
<td>21,555</td>
<td>34,528</td>
<td>22,460</td>
<td>16,840</td>
</tr>
<tr>
<td>Taiwan</td>
<td>26,122</td>
<td>25,664</td>
<td>22,600</td>
<td>20,442</td>
<td>22,060</td>
</tr>
<tr>
<td>Thailand</td>
<td>269</td>
<td>469</td>
<td>3,511</td>
<td>34,679</td>
<td>53,915</td>
</tr>
<tr>
<td>USA</td>
<td>9,709</td>
<td>44,402</td>
<td>8,431</td>
<td>7,835</td>
<td>8,184</td>
</tr>
<tr>
<td>Malaysia</td>
<td>12,259</td>
<td>11,056</td>
<td>8,544</td>
<td>11,211</td>
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</tr>
<tr>
<td>UK</td>
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<td>38,306</td>
<td>21,114</td>
<td>33,042</td>
<td>33,792</td>
<td>32,694</td>
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</table>

The two major segments of the motors market in Australia are:

- Original Equipment Manufacturers (OEM) or bulk market segment. OEM's purchase motors directly from the manufacturer or importer. It is estimated that this segment accounts for between 80% - 85% of up to 7.5kW AC motors sold in Australia. Local manufacturers and repairers of HVAC equipment are the largest users of bulk market motors.

- Project Market. These are generally motors >7.5kW and are used in larger-scale engineering projects in the building HVAC, mining and manufacturing sectors.

At present there is only one motor manufacturer in Australia with ability to produce electric motors at industrial scale, with single phase motors the vast majority of production. Over 350 businesses in Australia are directly involved in the supply chain, including importers/distributors/brokers, retailers/spare parts sellers, and motor repairers/
resellers. However there are 35 brands of motors and approximately 3000 individual models registered for sale in Australia under the MEPS regime.

A recent benchmarking study on motor efficiency (DEM et al, 2005) estimated that five major suppliers of motors in Australia (TECO, CMG, WEG, Toshiba, and ABB) provide 95% of the three phase electric motors up to 100kW. This same study suggests that TECO and CMG have larger shares in the OEM or bulk market segment, while WEG tend to have uniform shares across all size categories. Both Toshiba and ABB are estimated to have larger shares in project segment of the electric motor market.

4 MEPS Levels

Background

MEPS programs are made mandatory in Australia by state government legislation and regulations which give force to the relevant Australian Standards. Regulations specify the general requirements for MEPS for appliances, including offences and penalties if a party does not comply with the requirements. Technical requirements for MEPS are set out in the relevant appliance standard, which is referenced in state regulations. State based legislation is necessary because the Australian constitution gives Australian States clear responsibility for resource management issues, including energy

The National Appliance and Equipment Energy Efficiency Committee (NAEEEC), consisting of officials from the Commonwealth, State and Territory government agencies and representatives from New Zealand, is responsible for managing the Australian end-use energy efficiency program. The Committee reports to other government structures and is ultimately directed by the Ministerial Council on Energy (the Energy Ministers from all jurisdictions)

The policy relating to MEPS is as follows:

"Australia and New Zealand have adopted a best practice standards and labelling program and match the best MEPS and mandatory labelling levels of our trading partners" (AGO 2005)

MEPS levels for 2006

As such, the MEPS levels for electric motors will be introduced in April 2006 to match the levels of Canada and the United States, who currently have the world’s most stringent mandatory standards for motors, having adopted comparable standards in 1997. These North American mandatory standards actually correspond closely to the European Union’s CEMEP ‘Efficiency 1’ or EFF1 level, when testing differences are taken into account. The 2006 MEPS and High Efficiency (HE) levels to be introduced in 2006 are shown in Table 2 for Method B of the AS 1359.
Table 2: MEPS and HE for Motors in 2006 (AS 1359.102.1 or IEC60034.2 Method)

<table>
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<th>kW</th>
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<th></th>
<th>4 pole</th>
<th></th>
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5 Australia Market Impacts of MEPS

Energy and Greenhouse Emission Impacts

The first round of MEPS for motors was estimated to reduce energy consumption, compared to Business as Usual (BAU), by approximately 450 GWh pa and abate 450 kt pa of greenhouse gas emissions by 2015 (GWA 2000). The estimated effect of the 2nd round of MEPS to be introduced in 2006 is that an additional 550 GWh pa and 600 kt of GHG abatement will occur by 2015. The savings from the 2006 MEPS cumulate to over 7 Mt CO2-e greenhouse gas emissions between 2009 - 2012. (Syneca Consulting 2003)

Models Available

However the market impact of the this 2nd round of MEPS is estimated to be much greater for 2006 compared to the 1st round of MEPS introduced in 2001. Approximately 60% of models already complied with the 2001 MEPS levels in 1995 (when it was first proposed). In 2004, only 30% of the models currently on the market complied with the newly proposed 2006 MEPS. The effect of MEPS in 2006 will be a market
transformation of the available motor market in Australia to levels that are equivalent to the EFf 1 European label.

As expected the motor suppliers are already preparing for the introduction of the 2006 MEPS levels and now approximately 40% of models comply with the 2006 MEPS, as shown in Figure 1.

![Graph showing motor efficiency vs. power](image)

Figure 1: 4-Pole motor models by size complying with 2006 MEPS (DEM 2005)

6 Lessons Learned

Australia's experiences may assist other countries or economies when introducing or increasing the stringency of MEPS. Our strategy has been particularly effective by accommodating a range of approaches which has included: broad consultation with industry and government, detailed research to support MEPS levels, options of various pathways for MEPS compliance, support of internationally recognised testing methodologies and facilitation of industry compliance.

Consultation

As part of the initial consultation and research phase leading up to the implementation of the MEPS standards in 2001, a broad sector of industry and end users were consulted to inform them of the proposed strategy as well as providing the opportunity to seek feedback and suggestions on the implementation of the strategy. Meetings were held with groups such as Australia Electric Equipment Manufacturers Association and a specifically formed motor suppliers group. This consultation process helped facilitate the smooth introduction of the MEPS standards in 2001 and assisted in building com-
mitment to the proposed strategy as well as providing opportunities for these groups to feedback to Government how adjustments may be made to ensure greater acceptance of the MEPS.

Furthermore, the introduction of the 2006 MEPS was facilitated by the formation of a industry based steering committee that provided expert input on the proposed 2006 MEPS and implementation strategy. Industry was assured that these MEPS will be in place for a period of 4 years and consequently can plan to import motors with the surety of a stable regulatory environment.

Detailed Research

Before the introduction of the 1st round of MEPS, detailed research was conducted by the government focusing on the appropriate MEPS regime and levels. In the 6 years prior to 2000, 3 major reports on the MEPS program for Motors were released to industry and other interested stakeholders.

In preparation for the 2006 MEPS levels, a detailed analysis of the proposed MEPS was conducted (NAEEEC 2002a). The outcome of this research and the government proposals in for increasing the stringency of the MEPS, was provided for public feedback (NAEEEC 2002b). In both rounds of MEPS, a detailed Regulatory Impact Statement (RIS) was conducted to assess the benefits and costs of the proposed MEPS for Australia. The RIS is an important part of the Australian efficiency regulation framework and compiles the available research to ensure the MEPS satisfy the following criteria (Syneca Consulting 2003):

- The need to be cost-effective for the broad community of users.
- The need to be efficiently designed, minimising adverse impacts on manufacturers and suppliers, and minimising adverse impacts on product quality and function.
- The need to be clear and comprehensive, minimising potential for confusion or ambiguity for users and suppliers.

Alternative MEPS Compliance Approach

A key plank in the MEPS framework for motors is the allowance for motor suppliers to comply with MEPS using either of the two major international test methods. MEPS levels are provided in for both test methods as defined by Australian Standard A/NZS 1369.5. This ensures the costs associated with motors MEPS to be minimised as suppliers already test or calculate the energy efficiency of nearly all their products in accordance with either Test Method A or Test Method B in AS/NZS 1359.5. Given that either method may be used to demonstrate MEPS compliance or claim HE status, the extent of additional testing by suppliers is minor.

By utilising international recognised test methodologies and working closely with the organisations responsible for the development of these test methods, the Australian MEPS implementation regime is consistent with our major trading partners. These
Facilitation of Industry Compliance and Promotion

The Government facilitates the compliance of motor suppliers with MEPS via the targeted check testing of motors. These tests are conducted by a National Association of Testing Authority (NATA) accredited laboratory. To assist with the establishment of independent testing of motors in Australia, the government has offered financial support to independent laboratories that wish to accredit their MEPS testing facilities to NATA standards.

The government also assists with marketing of efficient motors by providing support for the Motor Solutions Online web site and database. The web site (located at http://www.greenhouse.gov.au/motors/index.html) aims to assist with motor selection and optimisation of motor systems for high efficiency motors by offering the following:

- Checklist and Reference manual
- System optimisation information and case studies
- Self Assessment Tool
- Motor Selector software.

7 Future Directions

Australia will endeavor to match international best practice when targeting the regulatory management of motor efficiency. In doing so, Australia will pursue the following approaches:

- Benchmarking motor efficiency (to be completed in 2005)
- Measurement to IEC 61972 (by 2010)
- Matching China’s requirements for High Efficiency Motors.

International Motor Benchmarking

Australia has commissioned a study to benchmark the efficiency of three phase electric motors in Australia and four Asian countries: Thailand, Malaysia, China, India. The results of the data collection and analyses shows that of the five countries, Australia has the best, and China the worst average motor efficiency over the range of motor sizes analyzed. Thailand Malaysia have comparable market characteristics as regards efficiency (DEM 2005). The results of these benchmarking studies will be used by Australia in implementing its policy of “international regulatory best practice” in the establishment of minimum energy performance standards.

IEC 61972

The measurement and testing standards applicable to MEPS are prepared by the Joint Standards Australia/Standards New Zealand Committee EL-046, Rotating Electrical Machinery—Efficiency. This committee is now redrafting the AS/NZS 1359.102.3, Rotating electrical machines—General requirements—Methods for determining losses and efficiency—Three-phase cage induction motors and the equivalent IEC Standard.
61972, Method for determining losses and efficiency of three-phase cage induction motors. EL-046 is reviewing IEC 61972 for adoption as a Joint AS/NZS Standard to replace AS/NZS 1359.102.3.

IEC 61972 is a current IEC standard and it describes the measurement of losses and efficiency in an equivalent manner to the IEEE112 Method B which is used in North America. The IEC committees are currently reviewing IEC 60034-2 and 61972 is likely to be incorporated within it as the preferred method of testing for losses and efficiency.

Once this is the case there will be uniformity between the North American and EU standards. The IEC is the dominant International standard and ultimately there will be uniformity. The Australian MEPS method of compliance will ultimately insist upon testing to the present 61972. It is understood that full compliance with the new IEC standard will be difficult, as it requires the establishment of sophisticated and more accurate testing equipment. The Australian government will also determine ways to assist European suppliers fulfill Australian marketing requirements using IEC 61972 test reports, as an interim process.

High Efficiency Motor Levels

The High Efficiency levels for 2006 are based on a 15% reduction of losses from the 2001 High Efficiency levels. This HE level was determined as no other economy had specified an efficiency level that was sufficiently more stringent than the MEPS level and could be used to identify HE product. It is understood that China has recently proposed a new HE level for motors sold in that country. These methods and levels will be examined in detail and the Chinese HE levels adopted in Australia if these are appropriate for the Australian market.

Future MEPS levels

As Australia is a net importer of motors and we represent only a small proportion of the world market for motors, Australia needs to match international best practice, rather than create the MEPS levels that other countries follow. In this regard, Australia will monitor developments in other economies closely and establish the next MEPS levels in line with mandatory international best practice efficiency regulations. The current 2006 MEPS will be reviewed over the period to 2008, with the intention of implementing more stringent MEPS (if required) in 2010.

8 Conclusions

The Australia Government has broad experience in introducing MEPS for motors and has introduced two rounds since 2001. The MEPS have been implemented in consultation with industry and with a view to considering international best practice for MEPS based on the internationally leading standards. This approach has assisted in gaining support for and compliance with Australian MEPS by industry. In future, Australia will endeavor to match international best practices when targeting the regulatory manage-
ment of motor efficiency. This will be achieved by monitoring developments in other economies and establishing future MEPS levels in line with mandatory international best practice efficiency regulations.

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Energy Efficiency Standard Making for Small and Medium-sized Electric Motors in China

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Abstract

Electric motor systems consume over 50% of electricity nationally. China has a large potential of energy conservation on motors. The formulation and enforcement of an energy efficiency standard for motors is an effective way to save electricity. The energy efficiency standard for small and medium-sized electric motors was published by the Chinese government in 2002 with the mandatory minimum efficiency level equivalent to the eff2 level of Europe. The revision of the mentioned standard has been ongoing since 2004. In the new standard, the proposed mandatory minimum efficiency level will be equal to the eff1 level of Europe. This paper introduces the market status and energy conservation potential of electrical motors, barriers to the application of energy efficient motors, the former efficiency standard as well as an update on the new energy efficiency standard making process in China.

1 Market status and the energy conservation potential of electric motors in China

1.1 Market status

Most electrical drives in industry, commercial service, national defenses and public service are powered by electric motors. Nowadays, the total Chinese installation of motors was about 50 GW, which consumes more than 970 TWh annually, accounting for more than 50% of China's electricity use and 70% of industrial electricity consumption.

Along with the sustainable economic development of China, electric motor industry has been developing rapidly over the past ten years. In 2003, the output of three phase asynchronous motors was up to 97 GW. Figure 1 shows the outputs of three phase asynchronous motors over the past ten years in China.

At present, there are mainly two efficiency levels for motors in China, one is standard efficiency and the other is high efficiency. The standard efficiency motor has average efficiency of 87.3% which equals to Eff 2 of Europe, accounting for 93.5% of total motor production. The output of energy efficient motors with average efficiency of 90.3% equivalent to Eff 1 of Europe is only 6.5% of the market, in which more than 90% is for export. Energy efficient motors only hold about 1% of domestic sales.
1.2 Energy-saving potential

The total electricity consumption of China in 2020 is estimated at 4,360 TWh, of which 2,616 TWh will be consumed by motors.

If motor efficiency increases from standard (87.3%) to high efficiency (90.3%), the electricity saving potential for new build market will reach to 8 TWh per year by 2020, corresponding to the emission reduction of 7.2 million tonnes CO₂.

If total installed motors are replaced by energy efficient motors, 78 TWh will be saved, corresponding to the emission reduction of 70 million tonnes CO₂.

2 The situation of energy efficient motors in China

2.1 Barriers to the application of energy efficient motors

Most of motors are purchased by both of Original Equipment Manufacturers (OEMs) and end-users. In China more than 60% of motors buyers are not end-users but the OEMs. When they buy motors as their equipment drives, they mainly care about price besides power output and life. But the price of energy efficient motors is usually higher than that of standard motors. So the price is the most important factor that restricts the wide application of energy efficient motors.

The Chinese government enacted and implemented the motor efficiency standard the limited values of energy efficiency and evaluating values of energy conservation of small and medium three-phase synchronous motors in 2002. Due to high efficiency
level equivalent to Eff1 is only stipulated as a voluntary efficiency level in this standard, the market for energy efficient motors have been still to be developed.

Chinese end-users have had no much knowledge on energy efficient motors yet and their awareness of energy conservation through motor itself is waiting to be improved. Furthermore, the order of priority for purchasing is reliability, price, brand, energy efficiency and service. Reliability is a prerequisite for production continuity. Energy efficiency is not a key factor for motor purchasers.

2.2 The future plans of Chinese government

In recent two years, China has experienced the most serious electricity shortage it ever had. The government has made great efforts in policies making and enforcement to cope with the challenge. Electric motors, the largest electricity consuming equipment, were identified by the government as one of the important target for energy conservation. In November of 2004, The Energy Conservation Medium and Long Term Special Plan was published the Chinese government. This plan clearly points out the efficiency target of medium and small electric motors, namely the efficiency of those motors will be required to increase from 87.3% in 2002 to 90-92% in 2010. In order to reach this aim, the Chinese government launched the Electric Motors System Energy Conservation Project (EMSECP).

EMSECP includes mainly energy-saving alteration, running efficiency improvement, energy-saving technological application of electric motor and its system. To accelerate the replacement of inefficient motors and to encourage application of energy efficient motors, the concrete related measures consisting of establishment of the new efficiency standard and implementation of efficiency labeling system for electric motors were spelt out by this project.

3 Energy efficiency standard making for electric motors in China

3.1 Existing energy efficiency standard

As mentioned earlier the motor efficiency standard was published on January 1st 2002, and enacted on August 1st 2002. Two efficiency levels of motors were specified in this standard.

The mandatory efficiency level named Limited Values of Energy Efficiency is minimum efficiency level allowed nationally for motors, and all newly installed motors with efficiency lower than this value have been banned. This efficiency level equals to Eff 2 of Europe.

The voluntary efficiency level named Evaluating Values of Energy Conservation is a high efficiency value and a gist to evaluate energy conservation product and service for
the energy conservation product certification. This efficiency level equals to Eff 1 of Europe.

In fact the energy efficiency of all motors produced in China has reached the mandatory requirement by this standard. So it has no longer played an important role to move the motor market forward. It was agreed by Chinese government and motor industry that setting a higher mandatory efficiency target is very crucial for the country to save the energy in motor systems. A mandatory labeling system, which has been approved successful elsewhere, should applied to motors to help an effective enforcement. Therefore A new standard making process has been started since the end of year 2004 to take account of the above demands.

3.2 Proposed new motor energy efficiency standard

To promote the enforcement of energy efficiency standards, China has enacted mandatory energy efficiency labeling system starting from refrigerators and air-conditioners. Due to the mandatory requirement on energy efficiency labeling on product nameplate visible to buyers, consumers can easily identify the efficiency of the product and manufacturers can have a tool to differentiate their products from the competitors. Five grades of energy efficiency labels have been applied for home appliances and three grades were proposed for industrial products. It is proposed to set three grades of efficiency for motors in the new motor efficiency standard.

The first task for the new standard making is to determine the values of efficiency levels. So far a four-level methodology has been proposed to classify motor efficiencies in consideration of current availability of motor types at different efficiencies. Level 4 and Level 3 adopt same efficiency values as what the previous standard specified. For higher efficiency Level 3, the value was set as the efficiency of the motor with a total loss reduction of 15% over that of Level 3. Furthermore, Level 4 was assumed as the efficiency with loss reduction of 10% of that of Level 2. Figure 2 shows the four efficiency levels for 4-pole motors.

Apparent Level 4 and Level 3 correspond to Eff 2 and Eff 1 of European standard. Level 2 is basically same as the Australian “high efficiency” values stipulated in Australian standard AS/NZS 1359.5-2004 to be enforced in 2006. And Level 1 is very close to the Efficiency values of NEMA Premium Standard of the United States.

It has been proposed in the draft of the new standard that the government will take two phases of actions. At first phase, enacted immediately after the issue of the standard, three grades of motor efficiency will be adopted as Level 2 to 4, i.e. Grade 1 equivalent to Level 2, Grade 2 to Level 3 and Grade 3 to Level 4. At second phase, effective in three years after the issue of the standard, Grade 1-3 will equal to Level 1-3 respectively.
Figure 2: Proposed energy efficiency Levels for 4-pole motors in the new standard

The following Table 1 shows the relation between energy efficiency levels and grades. The mandatory level of Minimum Efficiency Performance Standard (MEPS) has been proposed to be Level 3 which equals to Eff 1 for the Phase 2 which will start from year 2009.

The first draft of new energy efficiency standard for motor has been formulated and according to plan the final draft will be finished by the end of 2005.

Table 1: The relation between energy efficiency levels and grades

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4 Conclusion

Electric motor systems consume over 50% of electricity nationally. China has a large potential of energy conservation on motors. The formulation and enforcement of energy efficiency standard and labeling system for motors are effective ways to save electricity.

The energy efficiency standard for small and medium–sized electric motors was published by the Chinese government in 2002 with the mandatory minimum efficiency level equal to the eff2 level of Europe.

The revision of the mentioned standard has been ongoing since 2004 and will be finished by the end of 2005. In the new standard, electric motors will be classified into three grades for energy efficiencies. Based on those grades an energy efficiency label will be required for each newly installed motor. The proposed mandatory minimum efficiency level will be equal to the Eff1 level of Europe and the high efficiency Grade 1 will be close to NEMA premium level of the United States.

5 References


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Policies and International Issues III
The Chinese Motor System Optimization Experience: Developing a Template for a National Program

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Abstract

Industrial electric motor systems account for more than 50% of China’s electricity use. If optimized, their efficiency could be improved by 20%. In response to this opportunity, China established a Motor Systems Energy Conservation Program in cooperation with the UN Industrial Development Organization, the US Department of Energy, and the Energy Foundation. A previous paper described progress at the mid-point of this pilot program. This paper presents the final results documented in case studies, and training activities and through a final independent program evaluation. The focus is on the efficacy of transferring complex system optimization techniques across languages and cultures using classroom instruction and hands-on measurement and assessment training in factories. Details are provided on lessons learned, including the strengths and weaknesses of the training model in preparing Chinese engineers to conduct plant assessments, develop projects, and train factory personnel.

1 Background and Introduction

This paper describes the China Motor Systems Energy Conservation Program, a technical cooperation project financed by Chinese government and industry, the United Nations Foundation (UNF), the United States Department of Energy (USDOE), and the Energy Foundation. The project was implemented over the period 2001 to 2004 by the Vienna-based, United Nations Industrial Development Organization (UNIDO) in cooperation with Lawrence Berkeley National Laboratories (LBNL), and the American Council for an Energy Efficient Economy (ACEEE).

UNIDO’s government counterpart in China was the State Development and Planning Commission (SDPC), subsequently reorganized as the National Development and Resource Commission (NRDC). UNIDO contracted with the China Energy Conservation Investment Corporation (CECIC) to supervise in-country activities. In turn, CECIC subcontracted with the Jiangsu and Shanghai Energy Conservation Centers who made local hosting arrangements for training, execution of plant assessments, systems optimization projects and case studies. Staff from both centers were among the participants in the training courses.

Equipment manufacturers have improved the performance of individual energy-consuming components such as motors, pumps, compressors and steam boilers, but these components only provide a service to the production process when operating as part of a system. Improvements to the efficiencies of motor systems often yield, in addition to energy savings, increases in productivity and reliability.
The program was as a pilot effort, which focused on Jiangsu and Shanghai provinces. It was designed to achieve significant energy savings in each province and also to provide a laboratory to test concepts for a nation-wide effort. The ultimate goal - the program’s development objective - is to control the growth of greenhouse gas emissions by establishing a national mechanism to promote motor system efficiency in industries throughout China. The program expects to achieve at least a 10% reduction in energy usage for each targeted motor-driven system.

Standard practice in the design of UNIDO technical cooperation projects requires the elaboration of measurable outputs which together contribute to achieving the desired program objective or goal. The China Motor Systems Energy Conservation Program was designed to deliver the following five outputs:

1. Training materials, motor system analysis tools, and systems standards developed, codified and available in Chinese and English languages.

2. Implementation networks established in each of the two pilot provinces in China.

3. A core group of national experts from each province trained in motor systems optimization.

4. Two provincial programs implemented, including specific goals for training programs delivered, systems assessments provided and projects/case studies completed.

5. Completion of an evaluation and elaboration of the national program.

Figures 1 and 2 shows the approximate distribution of the budgetary resources - provided by UNF - between each of the foregoing outputs and between the major groups of program inputs directly managed by UNIDO. Additional in-kind funding provided by USDOE, the Energy Foundation and Chinese sources brought the total program budget to about euro 2.32 million.
The planned independent program evaluation specified in output 5 was undertaken during and on completion of implementation. This paper benefits from this evaluation (2).

2 Effectiveness

2.1 Prerequisites for success

Several aspects of the program facilitated its successful implementation:

Firstly, it responds to promulgated government policy on energy efficiency and consequently enjoys the continuous support of both national and local government authorities. High level, local commitment facilitated the work of UNIDO’s subcontractors (the two Energy Centers) in establishing networks and delivering the municipal and provincial programs as required by outputs 2 and 4. Since the program was part of a broader scheme involving complementary inputs from US and China, it benefited from additional (non-budgetary) inputs in the form of knowledge and expertise from a wide range of sources. UNIDO’s prime contractor for the program (CECIC) is the most prominent Chinese agency in energy efficiency investment.

Significant UNF resources (57%) were dedicated to preparation for, and delivery of, training as defined in outputs 1 and 3 (fig.1). Twenty six percent of the UNF funds were used to field the international training staff (fig. 2). However, additional USDOE in-kind co-funding (€348,000) was made available to augment the budget for international expertise. Adequate funding of the training components assured the availability of high quality trainers who were both technically experienced and excellent communicators. One initial impact of high quality training was to secure the full commitment of senior officials from the two Centers. These senior officials participated actively in several of the training modules, which in turn served as an inspiration and motivation to Center staff. It also facilitated marketing system optimization services to the Centers' clients. Participants also included several factory-based energy engineers who became in-
instrumental in developing system optimization projects in their own facilities, frequently in cooperation with Energy Center staff.

Both Centers view energy systems optimization as a new business opportunity and their sense of ownership for the program resulted in commitment beyond their duties as UNIDO subcontractors. Knowledge and skills acquired through the UNIDO program enable them to offer improved services to their clients. In turn, commitment from clients (who are concerned about competitiveness), led to increased commitment of all the trainees.

2.2 Effective Delivery

The program initially developed and translated training materials on motor system optimization. This was followed by in-country training by international experts in motor system optimization. Along with the training, the international experts conducted factory visits in each province to demonstrate application of the principles taught in the training sessions and to instruct the experts in the use of measurement equipment purchased for each Center as part of the China Motor Systems program. Training focused on pumps, fans, and compressed air systems. The program was designed to accommodate learning by doing through practical, on-site training. The importance attached to industrial plant evaluations and to the development of projects and completion of case studies based on real investments helped trainees to recognize the importance of obtaining results.

Information about systems optimization is, to some extent, available in the public domain but its successful application requires a rigorous campaign of training for specialists and awareness building for a wide range of stakeholders, particularly plant managers and equipment suppliers. To overcome company level barriers, industry managers must be convinced that energy efficiency investments, including system optimization and plant assessments, save enough money to make them worth doing. Benefits that resonate with managers include greater reliability and avoidance of expensive production interruptions caused by equipment failure as well as greater production capacity through more effective use of existing equipment. Management support is required to link the capital cost of equipment with operating costs in order to implement a life cycle cost approach to system upgrades.

In the China Motor Systems program training was delivered to two groups of recipients:

- Training to prepare Chinese experts (Center staff and key plant energy engineers) to conduct plant assessments for industrial energy system optimization.
- Training for factory personnel so that they understand the benefits of undertaking system optimization investment projects.

In the first case, training materials (course content, software tools and delivery methods) were developed with the long-term goal of transitioning responsibility for delivering the training from the international team to Chinese experts.
The second type of training materials was designed for the use by the Chinese experts in delivering an “awareness level” system optimization training for factory personnel. These training materials provide an overview of a topic, such as pumping system optimization, in a one-day seminar.

The intensive experts’ training took care to avoid “ready-made” solutions. Variable speed drives, for example, although a useful means of avoiding the energy losses created by throttling valves, do not fit all circumstances. Trainees were taught how to identify problems, develop a measurement plan, collect and analyze data, and make recommendations to address identified problems.

Considerable emphasis was attached to problem solving through team-based challenges. Close interaction between the Chinese trainees and the international team of trainers was central to the program’s success. Building on cultural norms, senior participants were engaged as co-trainers. Training went beyond the traditional pedagogic approach of formal lectures. Exercises were designed to gain class participation. For example, opportunities were created for the Chinese trainees to present their findings from factory-based system optimization exercises to their colleagues and to the foreign experts and then to discuss their observations as a group.

2.3 Lessons learned

- Adequate preparation for each in-country training module is critical. Sufficient time must be made available in advance of each module to mobilize industrial plants to host practical training sessions. The process used for the UNIDO pilot included identifying two-three potential in-plant training sites and sending some preliminary information about the sites to the instructors in advance. The international team arrived one week in advance of the actual training to visit the proposed sites with Center staff, walk the system, meet with and interview the plant managers and engineers, discuss training logistics, prepare systems for taking measurements (e.g.- line taps) and take preliminary measurements. Final selection of training sites was made in cooperation with the Center staff. Factors considered included whether the system was suited for illustrating optimization techniques, the physical logistics of working with a group of students around the system, and management support.

- The China Motor Systems program modules consisted of one-week blocks of time dedicated to intensive training on the optimization of one system. The need to compress in-country training into one-week blocks and deliver sufficient information for system optimization is a major challenge. Modules must be carefully planned to maximize learning during each one-week period.

- Adequate training on project financing should be given equal priority with technical training. Trainees can find it difficult to translate engineering results into business financials.

- Training to adequately prepare an individual to conduct system optimization assessments is resource-intensive and best suited to developing a small cadre of
skilled professionals to work with plant personnel. At key organizations, several people should be trained, since some trainees will move to other jobs.

- Follow up between trainees and trainers is critical including follow-up visits, supplemental training, and regular email contact. With limited resources and over long distances this can be a challenge.

2.4 Results (Plant Assessments and Case Studies)

The first 38 industrial plant assessments completed by Chinese engineers, who received system optimization training identified nearly 40 million kWh in annual energy savings for an average per system savings of 23%.

Table 1 shows the specific goals and the status of the two centers in December 2004.

Table 1: Achievements of Centers

<table>
<thead>
<tr>
<th>Goals</th>
<th>Jiangsu Status</th>
<th>Shanghai Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Train 10 Motor System Optimization Experts (5 per Center)</td>
<td>&gt; 10</td>
<td>&gt; 10</td>
</tr>
<tr>
<td>Complete Plant Assessments for 34 Factory Enterprises (17 per Center)</td>
<td>18</td>
<td>23</td>
</tr>
<tr>
<td>Implement 8 Demonstration Projects with Case Studies (4 per Center)</td>
<td>4 completed, 8 underway or planned</td>
<td>4 completed, 3 planned</td>
</tr>
<tr>
<td>Train 200 Factory Enterprise Personnel per Center</td>
<td>&gt;700</td>
<td>&gt;200</td>
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</tbody>
</table>

Additionally, as a direct result of a study tour to the USA, the Shanghai Energy Center developed an internship program for senior year university engineering students.

A pump system optimization project, undertaken by the Shanghai Center in cooperation with the New Asiatic Pharmaceuticals Co., offers an illustration of a typical case study. This company, established in 1926, manufactured a total production value of 3 billion RMB (€280,500,000) in 2001. It uses 16.98 million kWh annually in a cooling water system with 4 parallel pumps each of 160 kW capacity. Three pumps operate continuously, one provides backup.

A plant assessment by the Shanghai Center determined that the pumps were oversized and also unable to respond to seasonal variations in load. The assessment also identified improper pipe configuration at pump inlet and outlet and inadequate performance of the heat exchangers. The center installed 2 new pumps with proper head and flow rate, redesigned inlet and outlet configurations, installed a variable speed drive and automatic control system and introduced cooling water treatment to clean pipes and heat exchangers.
The Shanghai Center invested 1.2 million RMB in project cost under a shared savings arrangement-80/20 over 3 years (80% to ESCO, 20% to end-user). Energy savings were 1.05 million kWh or 49% of system energy usage. Cost savings were 660,000 RMB (€62,000) annually with a 1.8 year payback.

A project undertaken by the Jiangsu Center in cooperation with SINOPEC Yangtze Petrochemical Company offers another example of the benefits of a system optimization approach. The company has 34 production areas with a total production capacity of 8 million tones per year crude oil refining, 6.5 million t/a ethylene, 300 thousand t/a Ethylene Glycol, 7.70 thousand t/a plastic, 8.5 thousand t/a aromatic hydrocarbons. In 2003 the Energy Center and the company conducted a system assessment which determined that the material supply and consumption in the production chains were not in balance. As a result, the pumps were oversized and throttle valves were frequently used to regulate fluid flow and pressure, thus wasting electricity.

The project included the installation of 34 VSD on 34 motors for the material pumping system. On project completion, the specific energy consumption was reduced from 8.016 kWh/t to 5.766 kWh/t crude oil refined, with estimated annual electricity savings of 14.08 million kWh, and 11270 tons of CO2 emission reduction. The simple payback period is 0.48 years. The plant has experienced additional cost savings from reduced maintenance and prolonged equipment life, as well as improved working conditions due to lower noise levels.

3 Sustainability

Outputs 2, 4 and 5 were designed to provide for continuation of efforts to optimize industrial motor systems in China beyond project completion. About 43% of the total budget was dedicated to this task, (figure 1).

3.1 Developing the Market

Shanghai and Jiangsu Centers have been in existence since the mid-1980s as part of the Chinese government response to a need for energy conservation and regulations established at that time, which the Centers help industry comply with. The Jiangsu Center serves industrial enterprises throughout the entire province of Jiangsu—102,600 square kilometers. The Jiangsu Center identified thirteen cities in Jiangsu province in which to conduct workshops, plant assessments and undertake projects. The Shanghai center, in contrast, serves a smaller geographical area, 6,200 square kilometers including the Pudong development area and the metropolitan area of Shanghai. The provinces are located adjacent to each other but it takes about four hours by express train and about 6 hours by car to travel between the Centers.

Jiangsu province has a population roughly four times the size of the municipality of Shanghai. The types of industrial enterprises operating in the two areas are quite different. Shanghai is a major port and has attracted a significant amount of western investment capital. Two industries targeted by the Shanghai Center are pharmaceuticals
and automobiles. Jiangsu has many large industrial enterprises, yet they are scattered across the province and represent a diversity of industries leaving no obvious industry group on which to focus. However, the Jiangsu Center used its expertise and contacts to somewhat target heat and power plants that provide electricity and district heating to industrial enterprises in their communities.

As a consequence of these pronounced differences in clientele served by each Center, they developed different business models to deliver system optimization services. These models also reflect the organizational strengths and business goals of each center.

Shanghai has established an Energy Services Company (ESCO)-type business model and intends to become the source of expertise that is currently lacking in local manufacturing plants. Shanghai manufacturers, that are not state-owned, run a western style, lean operation. Plant personnel are focused more on production than the operating energy sub-systems of the factory. The Shanghai Center wants to offer energy sub-system expertise and wants to share the energy savings achieved by implementing projects based on their analysis and recommendations. For Shanghai, offering factory training is a “means to an end” attracting new prospects for the Energy Center’s services, including project financing.

Jiangsu offer training and technical assistance to plant personnel for a fee enabling them to develop and implement their own energy savings projects and programs. In Jiangsu there is a mature manufacturing base (with some newer joint venture projects) whose culture is quite different from Shanghai’s. In Jiangsu, plants have a large staff that includes people dedicated to operating the plant’s energy sub-systems. For the Jiangsu Center, training and assisting factory personnel offers a cost-effective way to generate energy awareness and encourage factories to identify and undertake energy efficiency projects.

Shanghai’s approach to the market will likely produce larger per-plant energy savings, but since the Jiangsu Center should be responsible for generating many smaller projects, the total amount of energy saved may be as large or larger. To effectively realize and document these savings, Jiangsu must institutionalize regular follow-up with factory personnel who have undergone training, perhaps using the possibility of recognition as an incentive for post-training reporting.

Another consideration is that Jiangsu’s approach makes factory personnel responsible for identifying and correcting inefficient energy practices. This may result in an operating culture change that will sustain the initial energy savings. The Shanghai approach involves fewer factory personnel and may not result in an operating culture change. Without a thorough understanding of why system changes were made, Shanghai’s customers may revert to old operating practices and negate the energy savings, which could become a major issue for shared savings arrangements. Shanghai will also need to develop a follow-up program, possibly an annual one-day walk through, to ensure that their customers are maintaining their energy savings, sort of an audit maintenance agreement.
3.2 Standards – the Top-Down Component.

Seventeen percent of total UNF funds were used to develop training materials as required by output 1 (fig.1). This also included the substantial revision to a standard for the economic operation of three-phase motors and a separate standard for the economic operation of pumping, fan, and compressed air systems. Both standards are undergoing a public comment period and will be issued in early 2006.

This limited effort reflects the program goals of developing capacity in the two Energy Centers to sell market-based training and/or energy efficiency services to industrial clients rather than seeking to institutionalize sustainability through government intervention. As work on the program proceeded, the importance of a parallel effort to provide government support and recognition through system and energy management standards became evident. Additional support was sought and secured from the Energy Foundation to complete work on revisions to the system standards.

The limitations of relying primarily on the market to carry forward system optimization efforts lies in the fact that most optimized systems lose their initial efficiency gains over time due to personnel and production changes. The system optimization knowledge typically resides with an individual who has received training - detailed operating instructions are not integrated with quality control and production management systems.

Since production is the core function of most industrial facilities, it follows that the most sophisticated management strategies would be applied to these highly complex processes. Successful production processes are consistent, adaptable, resource efficient, and continually improving - the very qualities that would support industrial system optimization. Because production processes have the attention of upper management, the budgetary disconnect between capital and operating budgets is less evident. Unfortunately, efficient use of energy is typically not addressed in these management systems in the same way as other resources such as labor and materials. The answer lies in fully integrating energy efficiency into these existing management systems.

The International Organization for Standardization (ISO) has established management systems (ISO 9000 and ISO 14000) that are widely adopted in many countries including China. These standards, are used internationally as a trade facilitation mechanism, are already accepted as a principal source for standards related to the performance of energy-consuming industrial equipment, and have a well-established system of independent auditors to assure compliance and maintain certification.

It should be possible to establish a link between ISO 9000/14000 quality and environmental management systems and industrial system optimization based on the creation of a framework. This includes energy efficiency standards, policies, training, and tools that have the net effect of making system optimization for energy efficiency as much a

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1 As of December 2003, the latest published data, 500,125 ISO 9001:2000 and 66,070 ISO 14001 certified companies were participating in 149 countries. Extracted from The ISO Survey of ISO 9001:2000 and ISO 14001 Certificates- Thirteenth Cycle: Up to and Including December 2003.
part of typical industrial operating practices as waste reduction and inventory management. This proposal is discussed in another paper (3).

Through the delivery of comprehensive capacity building on systems optimization, the China Motors program has taken a first step in transforming Chinese motor systems industries to a systems orientation. Long-term success will require a permanent change in corporate culture using the structure, language, and accountability of the existing ISO management structure.

References


Motor Efficiency Improvement Initiatives in India

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Abstract

With expectations of large population growing, developing countries like India are finding it necessary to provide electricity to masses at affordable prices. The surge in demand overloads already weak grids resulting in very low voltages and forced load shedding. Government of India is trying to control increase need of energy for various activities through the formation & actions of Bureau of Energy Efficiency (BEE).

Indian National standard for Energy efficient motors has been revised on the line of CEMEP agreement with EU. Greater awareness on the need for Energy Efficiency has been created by the efforts of IEEMA (Indian electrical & electronics Manufacturers’ association) along with ICA (International Copper Association) & BEE. Indian manufacturers have also taken initiatives to introduce high-end energy efficient products such as Eff1 motors compliant with CEMEP norms, Epact compliant motors for North American markets & also novel products.

One novel product was the commercial introduction of permanent magnet based brushless DC fans in Indian Railways inspite of higher costs compared to conventional DC fans. The other initiative is the work started on development of motors with die cast copper rotors. The paper discusses the learning experiences in the introduction of such products & also the activities of the BEE in the field & future actions being planned.

1 Electricity Generation & Demand

1.1 Generation Capacity in India

One of the indices used to measure development of a country is per capita consumption of electricity. It is not an absolute measure of industrialisation as the pattern of usage depends on climatic conditions, relative costs of alternative energy sources & life style of majority of population. On the other hand, electricity consumption for industry is more indicative of the degree of industrialisation in the country. In India, there has been a steady increase in Electricity generation capacity over the years as can be seen from the table below. However, there is a shortage on peak demand capacity to the extent of 12 to 20 % since 1990

Table 1- Capacity of Electricity Generation in India (March End)

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</thead>
<tbody>
<tr>
<td>MW Installed</td>
<td>1711</td>
<td>3873</td>
<td>14326</td>
<td>28881</td>
<td>63637</td>
<td>94941</td>
<td>101630</td>
<td>104917</td>
<td>107972</td>
<td>112058</td>
</tr>
</tbody>
</table>

Source: Annual Report, Ministry of Power & 15th Electric Power Survey of India
1.2 Consequences
While capacity is growing, demand is growing at a faster pace. Reasons attributed are many - Growth of industry which is coming out of recession, population growth etc. With spread of TV thr'o cables & more than 100 channels, aspirations of people have gone up. India is also having one of the highest percentage of young people who are also better educated than their parents and want higher income, good things of life and comfort which is possible thr'o electricity. While electric motor driven pumps are used to irrigate farms & particularly cash crops like sugarcane & grapes; fans, airconditioners & home appliances provide comfort.

The problem got compounded with election promise by some winning coalitions to supply free power to farmers. This resulted into demand increase as wastage increased. Generation capacity was totally inadequate resulting in forced load shedding in Maharashtra during summer when Hydro power generation is low, lasting from 2 to 8 hours, particularly in towns and villages creating unrest with law and order problem.

1.3 Energy Conservation Act 2001
Fortunately, the Government of India had realised the danger of unsatiable & unmanaged growth of demand for electricity and other forms of energy. An Energy Management Centre was established first by the ministry of Power, that helped in identifying the problem & in formulating the proposed Energy conservation act. Energy Conservation Act 2001 was published in October 2001 & was brought into force with effect from March 2002 along with establishment of Bureau of Energy Efficiency (BEE).

1.3.1 Important features of the EC act are
- Standards & labelling- to lay down norms, create awareness, prevent manufacture of less efficient goods etc
- Designated Consumers- who are energy intensive & would be required to have compulsory energy audit in future & bring down energy consumption within prescribed norms per unit of production etc
- Certification of energy Managers & Accreditation of Energy auditing Firms
- Energy Conservation Building Codes
- Central energy Conservation fund to provide thrust to R & D to boost energy efficient equipment's
- Formation of Bureau of Energy Efficiency (BEE) as the main organisation to provide thrust on energy conservation
- Defined Roles for Central & State Governments towards Energy Conservation
- Enforcement through self regulation and
• Penalties & adjudication stipulating penalties in case of violations & adjudication in case of penalty imposed.

It can be seen that the act is very comprehensive. Actions are voluntary in the initial period & the act will have its teeth from 2007 onwards when penalties will be applicable. As per the latest estimates, it has helped by reducing demand by approx. 630 MW.

1.4 Bureau of Energy Efficiency

1.4.1 BEE Mission

The mission of BEE is to institutionalize energy efficiency services, enable delivery mechanisms in the country and provide leadership to energy efficiency in all sectors of economy. The primary objective would be to reduce energy intensity in the Indian Economy. Provide a policy framework and direction to national energy conservation activities, coordination, and establishment of systems for energy audit, labeling & promotion etc. BEE has initiated actions on several fronts & also provided thrust to formulate standards for popular sizes of AC motors.

1.4.2 BEE Activities on electric Motors

The Bureau has formed technical & executive committees for various products to go into depth from techno-commercial angles. The author is the Chairman of the committee for motors for which a number of meetings were held. After deliberations it was decided that IEC 60034-2 would be followed for labelling of motors at this stage and not IEC 61972. A list of popular ratings was drawn from which top 9 ratings have been selected for the initial stage of labelling for standard supply condition motors & 4 ratings for wide voltage variation (+10/-20%) motors. Efficiency Norms for motors for pump sets have been also agreed upon. It was also decided that the Testing authority would be BIS .IS 12615:2004 would be followed as a reference standard.

2 Energy Conservation Drives by Industry Organizations & other Non Government Agencies

Even before the government of India became active, IEEEMA (Indian Electrical & Electronics Manufacturers' Association) had realised the need & had started an Energy Conservation Cell. Electric motors form the highest portion of electric consumption in India consuming approx.70% of units consumed in industries. Therefore, main thrust was on motors. An initiative was taken by IEEEMA Rotating Machines Division by formulating IEEEMA standard 19:2000 for Energy Efficient 3 phase, squirrel cage induction Motors.

The standard covers full range of induction motors as covered by CEMEP agreement with EU. In addition, it also covers frames IEC 71& 80 for ratings 0.37kW & above upto 0.75 kW & also Frame 315 to cover ratings above 90 kW upto 160kW for 2 & 4 poles.
The standard also covers 6 pole motors from 0.37kW to 160 kW & 8 pole from 0.37 to 132 kW ratings. It lays down norms for so called nonstandard motors (e.g. 50 °C ambient) & stipulates minimum Breakaway torque & maximum starting current in view of weak grid conditions.

The standard set the norms for Energy Efficient (EE) motors & was subsequently adapted by Bureau of Indian Standards to formulate IS 12615:2004 with minor changes.

A major role was played by M/S ICPCI (Indian Centre of the International Copper Association Limited) in the propagation of the concept of Energy conservation in Electric motors. They organised many seminars along with project partners, which included Bharat Bijlee, Crompton Greaves & Siemens India as Indian motor manufacturers. The seminars were held for users, OEMs & consultants all over India & made the users aware about IEEMA standard 19:2000 & the concepts of Eff2, Eff1 & advantages of using EE motors and payback.

3 Current Status of Energy Efficient Motors in India

3.1 Standard

While initial response was not encouraging as many considered EE motors as a luxury due to their higher price or as a fad being propagated by developed countries, the efforts put in have started yielding results. IEEMA members took a conscious decision to offer Eff2 motors as a standard. One major problem faced was the endorsement of EE norms by Bureau of Indian Standards. The revised standard IS 12615:2004 was printed & available only from End March 2005. It covers motors upto Frame 315 unlike CEMEP agreement with EU. For ratings which are common for both standards, the efficiency levels are same and motors are tested to the same standard i.e IEC 60034-2.

3.2 Findings & Problems encountered

Some customers compared efficiency figures for only some ratings & came to the erroneous conclusion that Eff2 was not different than earlier standard motors offered by reputed manufacturers. In practice, manufacturers had to improve earlier designs in many cases, particularly for the smaller ratings to meet the improved efficiency norms & restricted starting currents & incurring higher costs for which customers were reluctant to pay more.

Another problem being faced by manufacturers recently is the availability of low loss core material as and when required at reasonable rates when the demand for Eff1 motors has started to pick up.

The third problem being faced by the motor manufacturers is the steep rise in the price of copper, which forms a higher percent of total material costs in case of EE motors.
Customers are again less willing when the price difference is higher between standard & EE motors.

3.3 Usage

Inspite of the problems, propagation of EE motors has started delivering results. More industry people are aware about the concepts of Eff2 & Eff1. Project consultants have started to specify Eff1 motors for new projects. Some people have gone even further. One modern Pharma Company (Ranbaxy Labs) asked for Eff1 motors in flameproof construction in large quantity and the demand was fulfilled by the organisation of the author.

4 Other Initiatives in EE Motors in India

4.1 Epact Compliant motors

While efforts were on to develop & propagate EE motors to CEMEP / IEEMA standards, it was observed that Epact compliant motors have a much larger market. However it called for different type of testing to IEEE 112 B / CSA 390 which requires more sophisticated & precision class instruments. The author's company took the lead & has developed a complete range of such motors upto 200 hp.

4.2 Induction Motors with Die cast Copper Rotors

As copper has higher conductivity than aluminium, it is used in large motors having fabricated rotor construction where diecasting of aluminium is prohibitively expensive. It is also used in submersible pump motors where diameters are small & there is not enough space to accommodate large aluminium sections to reduce losses. ICPCI have been propagating the concept of diecast copper rotors. One foundry in western India has developed technology for pressure diecasting of small copper rotors. Tests carried out on sample motors show that efficiency improvements take place & it will be easier to obtain Eff1 with less or minimal changes in the geometry of stampings. However, concerns about overall costs, assured availability & small market size for Eff1 motors have resulted in limited implementation of this technology so far.
5 Energy Efficient Permanent Magnet Brushless DC fans for Indian Railways

5.1 Rationale

Only DC supply was available on Electrical Multiple Units used on the Mumbai suburban coaches & most of old main line trains. The rationale here was to have energy efficient motors, which are maintenance free, & with less weight reducing haulage energy costs. Use of induction motors with drive would have still resulted in rotor loss due to slip keeping down overall efficiency inspite of high cost of induction motor drive.

5.2 Development

The organisation of the author, Crompton Greaves Ltd, Mumbai, supplies all types of electric equipments for Indian Railways- Traction transformers, traction motors & generators etc. The company is also famous for its wide range of ceiling & table fans in the premium category. Indian Railways were interested in getting supplies of high quality fans requiring less maintenance & the idea of developing a modern BLDC coach fan took birth. BLDC motor has electronic drive assembly as one of the key unit for satisfactory use. Maximum thrust was provided to ensure its reliability in addition to design of the motor for high efficiency. Samples were supplied & run on trains to evaluate the performance on EMUs & also on main line locos as the application patterns are different. Feedbacks were incorporated to arrive at the final design. A specification was evolved by RDSO (Research, Design & Standards Organisation of Indian Railways) for such fans. Final model was thoroughly tested by RDSO & cleared for more extensive use on Indian railways. With satisfactory field reports, Indian railways have started moving towards this type of fans.

5.3 Benefits

5.3.1 Reduction in total weight of assembly from 16 kg to 7.5 kg.

This reduces overall haulage weight by approx. 3.5 tonnes in a train. The haulage energy cost saving is INRs 3760 (Approx. $ 87) per fan per year. Thus full cost of a new fan is recovered within a year. It helps in installation cost as the weight is low as one person can fit the fan instead of two required earlier.

5.3.2 Reduction in power consumption from 36 watts to 32 watts & providing 20 % more air quantity.

The service value in terms of Air quantity Cu M per min / watts consumed has gone up from 1.5 to 2.
5.3.3 Minimal Maintenance needs

The fans are only hosed by water to clean dirt on blades as no maintenance of brushes is required. Requirement of maintaining brushes & brush-holders has also disappeared. Railway officials have found this as the best feature although reduction of energy costs is also a major factor, which weighs heavily in payback calculations.

5.4 Conclusion on BLDC Railway Fan Project

Technologies leading to less amount of weight to be hauled are likely to provide better pay back than only those with higher efficiency of motors alone.

6 Overview

- With high expectations of population in a democratic country, Indian government machinery at Central & State level has started realising the importance of Energy Conservation to make best utilisation of available resources. Necessary policy & legal framework is being set up to drive Energy Conservation.

- Industry organisations & manufacturers are also contributing by developing energy efficient products. Indian standard for Energy Efficient motors covers wider range than CEMEP. Eff1 & Epact compliant motors are now made in India.

- Energy efficient & more expensive products are purchased by customers if they feel real value for money in terms of payback period or other features such as reduction of need for maintenance in case of BLDC motors instead of DC motors with brushes.

7 References

Energy conservation Act 2001, Government of India


Challenge to Develop High-Efficiency Motors in Japan

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Abstract

1. Introduction
The challenge to develop high efficiency motors started in earnest in Japan after the oil crisis in 1973. Efficiency criteria for high efficiency motors were set before they were in other countries such as the United States and European countries, and then the efficiency standard for high efficiency motors: JIS C 4212 "Low-voltage three-phase squirrel-cage high-efficiency induction motors" was established.

2. Content
This paper reports the following.
1) Progress in development of high efficiency motors in Japan.
   The effect of energy reduction by improving the efficiency of motors is high. Thus, attention was focused on high efficiency motors and finally JIS C 4212 was established in July 2000 as the standard for high efficiency motors.
2) Standard values of efficiency and test methods are specified in JIS C 4212, which adopts the internationally used testing method.
3) Japan’s energy saving measures (factors in low rate of popularization of high efficiency motors)
   A major factor in the low rate of popularization of high efficiency motors is that the introduction of energy saving measures for application of power electronics preceded that of high efficiency motors.
3. Conclusion
Recently, the use of permanent-magnet motors as high efficiency motors has become more widespread in some applications. This indicates that each component itself also needs to be of high efficiency. In conclusion, high efficiency motors are “must” items from the viewpoint of preventing global warming.

1 Introduction
The challenge to develop high efficiency motors started in earnest in Japan after the oil crisis in 1973. Japan set efficiency criteria for high efficiency motors before foreign countries such as the United States and European countries, and then efficiency standard for high efficiency motors was established as the JIS standards for high efficiency motors.

This paper reports progress in our challenge to develop high efficiency motors together with standard values of efficiency and test methods specified in the JIS standard. Finally, it reports the dissemination of high efficiency motors in Japan.

2 Challenge to develop high-efficiency motors in Japan
As a result of the efforts of various motor manufacturing companies since the oil crisis, the Japan Electrical Manufacturers’ Association (JEMA) issued “Selection and Applica-
tion of Motors for Energy-Saving” in 1982 as its technical document No. 137, and presented the “Efficiency criteria of the TEFC motors for energy-saving” as shown in the attached table. These set the efficiency criteria for high efficiency motors. By 1982, no other countries had set such criteria. Thus, Japan was the leader in the challenge to develop high efficiency motors.

The Kyoto conference on prevention of global warming was opened in December 1997 in the midst of heightened concern for global environment protection. At this conference, reduction of emissions of greenhouse gases such as carbon dioxide became an international commitment. As a result, the “Law on rationalization of energy consumption” was revised in 1999, in which “Judgment criteria by enterprises regarding rationalization of energy consumption in factories” was disclosed, and efforts for energy saving in factories and offices were strengthened. The following two obligations were enforced:

1. For class-1 designated energy management factories, an obligation to create and submit future energy-saving plans was enforced.

2. For class-2 designated energy management factories, an obligation to rationalize energy consumption in accordance with the judgment criteria was enforced.

As a result of these obligations, the target for annual energy consumption reduction for each factory or for each enterprise was set at 1 percent or more in the middle and long term.

It is generally said that electric power consumption by motors in manufacturing factories is around 70 % of the total. Thus, the effect of energy reduction by improving the efficiency of motors was high. So attention was again focused on high efficiency motors. Finally, JIS C 4212 “Low-voltage three-phase squirrel-cage high-efficiency induction motors” was established in July 2000 as the standard for high efficiency motors.

The “Law on rationalization of energy consumption” was again revised in 2003 to reduce energy consumption causing carbon dioxide generation. The points of revision of this law were as follows:

1. For class-1 designated energy management factories, limitation of the target categories of industry was removed.

2. For class-2 designated energy management factories, obligation to submit regular reports was enforced.

The purpose of the law’s revision was to further reduce energy consumption by enlarging the target categories of energy consumption reduction. The efficiency values specified in JIS C 4212 “Low-voltage three-phase squirrel-cage high-efficiency induction motors” were presented as target efficiencies for motors. Thus, use of high efficiency motors is recommended.
3 JIS C 4212 “Low-voltage three-phase squirrel-cage high-efficiency induction motors”

3.1 Scope

The scope is shown below.
- Number of poles: 2, 4, 6
- Rated output: 0.2 kW to 160 kW
- Rated voltage: 200 V, 220 V, 400 V, 440 V
- Frequency: 50 Hz, 60 Hz, supporting both 50/60Hz
- Protection: IP4X (TEFC), IP2X (ODP)

3.2 Efficiency values

Table 1: Efficiency values of IP4X motors (Unit: %)

<table>
<thead>
<tr>
<th>Rated output kW</th>
<th>2-pole</th>
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<tr>
<td></td>
<td>50Hz</td>
<td>60Hz</td>
<td>50Hz</td>
<td>60Hz</td>
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<tr>
<td>200V or 400V</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>220V or 440V</td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>0.2</td>
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Unlike other countries, Japan has a 50 Hz power supply area and a 60 Hz power supply area. If a motor is designed for both of 50 Hz and 60 Hz operation, it is required to be operable in both areas. Thus, the efficiency standard values take these factors into
consideration. At the same time, motor efficiency changes depending on the efficiency testing method. The JIS C 4212 “Low-voltage three-phase squirrel-cage high-efficiency induction motors” adopts an internationally used efficiency testing method, as described in paragraph 3.3.

After the above investigations, the efficiency values specified by JIS C 4212 “Low-voltage three-phase squirrel-cage high-efficiency induction motors” are shown in Tables 1 and 2. Table 1 shows the efficiency values of IP4X motors and Table 2 shows the efficiency values of IP2X motors.

### Table 2: Efficiency values of IP2X motors (Unit: %)

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### 3.3 Efficiency testing method

The efficiency testing method uses the actual loading method, called the brake or dynamometer method, specified by the American EPACT (Energy Policy Act).

This method is executed in steps a to d as follows.

a. No load test

The motor is operated at its rated voltage and frequency. After the input power becomes stable, the voltage, current and input power are measured at various points be-
between a voltage slightly higher than the rated voltage and the lowest voltage that can maintain synchronous speed. The mechanical loss and iron (core) loss are calculated from the values measured at these points.

b. Load test

A motor is coupled to a brake or a dynamometer. The load is changed within the range of 25% load to 150% load. The input power, current, slip, torque and stator winding resistance are measured while the load is changed. These measured values are used to calculate total loss, primary resistance loss and secondary resistance loss.

c. Smoothing out stray load loss

The tentative stray load loss is calculated by subtracting primary resistance loss, secondary resistance loss, mechanical loss and iron loss from total loss. The stray load loss is smoothed out by executing a linear regression analysis to the square of torque.

d. Calculation of efficiency

The ambient temperature is fixed at 25 °C. The primary resistance loss and the secondary resistance loss are compensated using the temperature rise during the rated load operation. The efficiency is calculated using compensated primary and secondary resistance losses, mechanical loss, iron loss, and smoothed stray load loss.

As described above, a motor must be coupled to a brake or a dynamometer in the brake method or dynamometer method. This means that considerable time is required for measurement. However, measurement accuracy is high, and the measurement condition is very close to the actual condition, because the efficiency is measured, while load is being to the motor. Therefore, this measurement method is optimal for evaluating motor efficiency.

4 Japan’s energy saving measures (Factors in low rate of popularization of high efficiency motors)

According to a survey conducted in 2004 by the Japan Electrical Manufacturers’ Association (JEMA), 81.9% of industries in Japan recognize high efficiency motors, while 17.6% of industries recognize them, showing that awareness is very high. However, only 19.5% of that 81.9% replied that they intended to use them. Statistical results have also shown that the rate of popularization of high efficiency motors is presently low in spite of this high awareness. Although an approach to introducing high efficiency motors may be considered to be late, the legal requirements for energy saving in Japan are much more stringent than those implemented worldwide.

To meet the requirements for such energy saving, technical development of high efficiency motors has been advanced, aiming at world top-class reduction of power loss, while research and development have rapidly advanced in areas such as efficiency improvement at partial load of motors integrated with equipment by power electronics such as inverters themselves and inverter-driven technologies for permanent-magnet -
type synchronous AC motors, loss and cost reduction of devices available for popularization of inverters, and efficiency improvement in installations by application of inverters, etc.

As a result, to satisfy the control criteria for CO₂ emission determined by the COP3 held in Kyoto in December 1999, the situation in Japan is advancing as follows.

Standard motors have been exchanged for high efficiency motors, and in addition, systems as a whole have been improved by the introduction of variable speed, group control of motors, energy monitoring systems, etc.

Japanese industrialists preferably introduce an energy saving measure to apply power electronics to motor drive systems rather than high efficiency motors. This is due to the continuous and stringent requirements for energy saving in Japan. Therefore, the rate of popularization of high efficiency motors remains low.

As described above, a major factor in the low rate of popularization of high efficiency motors is that the introduction of energy saving measures for applying power electronics precedes that of high efficiency motors. This seems to be a factor particular to Japan.

5 Conclusion

Recently, the use of permanent-magnet motors as high efficiency motors is becoming more widespread in some applications. This tendency can be understood from the fact that each component itself also needs to be of high efficiency. Thus, we issued “Low-voltage three-phase synchronous motors with permanent magnet” in 2005 as standard JEM 1487 in order to disseminate permanent-magnet synchronous motors.

In conclusion, high efficiency motors are "must" items from the viewpoint of preventing global warming.
The Target Program for Three-Phase Induction Motors

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Abstract

Since 1992 INMETRO and ELETROBRÁS have worked hard in the energy efficiency area of three-phase induction motors. This effort has made it possible for them to be the first products to have minimum efficiency requirements for commercialization in Brazil. Motors regulation, enacted in 2002, is remarkable for ensuring the evolution of all efficiency levels reached until now. The country has evolved from having low technological standards to efficiency similar to that in developed countries. Brazilian regulation is innovative for prescribing the target program publication for continuous efficiency improvements. Here are presented the implementation and market evaluation related to the aim/target program.

1 Introduction

The National Labeling Program - PBE, coordinated by National Metrological Program - INMETRO, and the National Electric Energy Conservation Program – PROCEL, housed in Centrais Elétricas Brasileiras S.A. – ELETROBRÁS, with technical and laboratorial support from the Research Center on Electric Energy – CEPEL, have worked hard on the area of energy efficiency of electric motors since 1992. Allegedly, the process of setting minimum performance standards for three-phase electric motors has been done for the past 13 years.

The first standards of minimum performances were discussed about and agreed on as part of a volunteer agreement elaborated by a the working group on Motors within the PBE in 1998 and served years later as the basis for the PROCEL Energy-Saving Awards.

Law no. 10.295 was promulgated in 2001 and it concerned the National Policies for the Rational Use and Energy Conservation in equipments. It determined the setting of minimum energy efficiency standards or maximum levels of specific consumption for energy consuming machines and appliances that are manufactured and commercialized in the country.

In order to implement the Law, Decree no. 4059 was signed in 2001, in respect of procedures and responsibilities for the setting of minimum standards of energy efficiency and maximum levels of consumption. The Decree created the Managing Committee for
Indicators and Levels of Energy Efficiency – CGIEE. The Committee’s responsibilities are, among others, to elaborate specific regulations for each type of energy consuming equipment, to establish the Target Program with the indication of the evolution of levels to be reached by each regulated equipment and to create technical committees to analyze specific issues.

One year later, the regulation for industrial three-phase induction motors was promulgated.

2 Technical regulation of motors

2.1 Historic Overview

To initiate the elaboration of the specific regulation for energy-consuming equipments, the Managing Committee selected three-phase induction motors. The choice for this equipment is due to the significant electricity consumption potential that they represent in the energy consumption matrix – approximately 30% of the total consumption of the country, as shown in Figure 1, and approximately 49% of the total consumption of the industrial sector (Soares 2002), as presented in Figure 2. Besides, there is a consistent amount of data derived from the labeling process for efficiency and power factor. We were also concerned indeed that motors process instead of consume electric energy so complementary actions for motor loads have been done.

![Total Electric Energy Consumption](image)

Figure 1: Percentage of electric motors in the national consumption of electric energy

In June 2002 the CGIEE created the Technical Committee for Motors, responsible for the development of technical research to support CGIEE’s decisions.
Figure 2: Electric energy consumption in the industrial sector, with emphasis on motor driven power

This Committee formalized the work already done and elaborated the first official versions of the specific regulation. The results were thus taken to the CGIEE, which approved the regulation and submitted it to Legal Affairs Consultancies of the Ministry of Mines and Energy-MME, Ministry of Science and Technology-MCT and Ministry for the Development of the Industry and Commerce-MDIC.

The CGIEE determined the realization of a public consultation, widely broadcasted in the national media. It was fundamental both to make the process clear and to ensure the participation of all interested parts. The Technical Committee of Motors elaborated a report, available on the MME website, containing the answers/comments to all the contributions received during said public consultation.

The final stage of the work started with the elaboration of a Presidential Decree that approved the specific regulation and the Statement of Reasons. During this stage, the final version of the Specific Regulation of Motors was analyzed by the Legal Advisors of MME, MCT and MDIC. After the analysis, the Presidential Decree was signed on December 11th, 2002 – Decree no. 4.508.

Six months later, this technical committee started the work for establishing the target program. At the same time, a series of tasks was done to ensure the correct implementation of this Decree.

2.2 Guidelines to regulation

The regulation was based on the following pillars described below:

- **Big scope**: by this viewpoint, the following product types were included: motors that are part of other machines, all levels of protection, except those that are explo-
sion-proof, vertical and horizontal mountings, continuous operation with voltage below 600 V.

- **North-American Law**: the legislation was a valuable source of learning since the American law which ought to have gone into effect in 1997, took 2 years to be implemented. This process, which is well documented, avoided several difficulties that certainly would have also happened in Brazil.

- ** Guarantee obtained gains**: the gains in efficiency derived from the technological upgrade of the past 13 years were obtained by means of voluntary work; therefore the law ensured no turning back.

### 2.3 Presenting the Regulation of Motors

The specific regulation comprises three-phase squirrel-cage induction motors with power ranging from 1 up to 250 hp, voltage below 600 V, number of poles 2, 4, 6 and 8. Two categories of performances were defined on the regulation: standard and high energy efficient lines (Soares 2002) and (Soares 2003). The regulation also comprises motor-driven machines that operate with three-phase induction motors.

It is important to mention some differences between Brazilian, American and European products. Motors in Brazil and Europe have equal dimensions since they follow the sizes determined by the IEC – International Electrical Committee whereas American motors are usually larger because they follow the standards proposed by NEMA – National Electrical Manufacturer Association, especially those with lower power.

Brazilian and American motors are manufactured with 60 Hz frequency and European with 50 Hz. The test standards to determine performance are more stringent in Brazil and the United States, such similarity allowing a direct comparison of values.

Two sets of nominal efficiency values were negotiated with manufacturers: one for the standard line of motors and another for the efficient line.

The Brazilian regulation is characterized as innovative because the law prescribes a mechanism for the evolution of performance through the Target Program and it has bigger scope including approximately 80% of the market (Soares 2003). No international regulation prescribes the mandatory elaboration program to indicate the evolution of established minimum efficiency values.

### 3 Elaboration of the Target Program

In order to comply with the specific regulation of motors, the Technical Committee of Motors started the work to elaborate the Target Program in July 2003. By the motor regulation decree, the target program should be published in the end of 2003.

The suggestion for Target Program was centered on the minimum efficiency values for the current energy efficient motors. It indicated only this set of minimum efficiency lev-
els for three-phase squirrel-cage induction motors that would be manufactured and commercialized in the country in the next future.

The Technical Committee conducted a survey with national manufacturers through which it was possible to check their experience on making energy efficient motors and the technical feasibility of the suggestion. Issues like assessment of the technical hurdles/difficulties of production and impacts on manufacturing costs were addressed. Additional studies were done to cover other technical and commercial aspects.

During the survey with manufacturers, it became clear that in order to bring the Target Program into reality, complementary governmental actions were identified such as stabilization of prices and characteristics of steel-silicon plates produced in Brazil, incentives for testing and research labs to be modernized and investments on human resources, training of technicians to allow them to use modern methods for designing and testing electric machines, and the modernization of computer tools (CAD software and finite elements techniques and so on).

The results of the survey and the studies were consolidated by the Technical Committee of Motors. The main conclusion was the suggestion was technical and commercial feasible, so this suggestion became an official proposal to take place in four years after the enactment. The Target Program as structured today will abolish the manufacturing and commercialization of current standard motors. Table 1 shows the set of minimum nominal efficiency values proposed.

The term for finishing the manufacturing of current standard motors and motor-driven machines using them is in 4 years’ time after Program has been published, whereas the deadline for commercialization is in 4 years and 6 months’ time due the stock. Before these deadlines go into effect, the current levels of the motors regulation are still valid.

The Target Program supports the structure of labs and testing policies as defined by the regulation. The test method to determine nominal efficiency is Dynamometric Test with indirect measurement of stray-load loss and direct measurement of stator, rotor, core, friction and windage losses in accordance with NBR 5383-1/2005 of the Brazilian Association of Technical Standards (ABNT) - Large Electric Machines – Part 1 – Three-Phase Induction Motors - Tests. This methodology is based on IEEE 112 – Method B and IEC 62893, so the results are comparable with those obtained with these procedures. The nominal efficiency ought to be determined in relation to the conditions of nominal tension, nominal voltage and nominal output power of the motor axis.

In order to ensure support to the implementation of the Target Program, the associated decree contains an article that determines the assessment and the follow-up of governmental actions. “CGIEE will be responsible for the follow-up and assessment of governmental actions in support of the implementation of the Target Program by Technical Committees of Motors and will elaborate reports twice a year that will allow for the verification of the feasibility to meet the requirements of this Edict and for proposing complementary actions so as to conciliate deadlines and the progress of governmental actions.”
Table 1: Proposed motors nominal efficiency minimum values of the Target Program

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3.1 Potential for energy saving of Target Program

In (Garcia 2003), a study was carried out to find out the energy savings potential of the replacement of all current motors in operation for energy efficient motors as stated in the regulation.

The following premises was considered to estimate the savings: the equivalent average national motor has a horsepower of 7.5 hp and operates with 75% of its nominal load (25% of the output rate is not use; an average operation time of 2,000 hours/year and a average time life of 12 years; total installed market of 12 millions of units; 1 million of replacement per year and the regulation comprises 80% of the motors market.

According to these premises, the annual energy saving resulting from the replacement of one motor was estimated around 1.58 TWh. That amount is equivalent to a hydraulic power plant of 365 MW operating on load factor 0.52 and 95% performance or a thermo power plant of 867MW operating on load factor 0.40 and 52% performance. Considering the price of US$30.00/MWh, annual saving will equal US$47.4 million.
3.2 Implications for the internal market

The main implications are:

- The existence of a single line of motors will cause restrictions to consumers when they decide/choose for a purchase. This will lead to the market expansion of the line presented in Table 1 which is that of current energy efficient motors.

- The need for investments of the manufacturers to migrate from their main production line (standard motors) to a line of high-efficiency motors, implying in revision of the logistics of raw materials, an adaptation of the processes and products in search for higher competitiveness without damage to the established goals and levels of productivity.

- One of the immediate impacts of the implementation of the Target Program is associated to an increase in manufacturing costs. Nowadays, the manufacturing cost of high-efficiency motors is approximately 25% higher than the cost of the standard model, as presented in Figure 3. The elimination of the production line of standard motors, associated with gains in the production scale and scope of the single product line, will result in an increase in the sales of high-efficiency motors. This increase will cut down the initial impact of 1.25.X to an expected final value “Y” equal to 1.10.X in a few years’ time. The accommodation time of the cost depends on governmental actions like financing manufacturers’ researches and improvements of the manufacturers’ plants, as described in the previous paragraph.

- Pressure for avoiding motor over sizing by better sizing motors in respect to the load in the industry facilities.

![Figure 3: Estimates of the time evolution of manufacturing costs of motors after the Target Program](image-url)
3.3 External Market

Essentially, the efficiency levels of Target Program are those used by North American Law and EFF1 European motor table. It is believed that this will facilitate the commercialization of the products in the external market as gains of scale will occur and this is also a strategic market issue as Brazilian manufacturers are exporters too.

4 Conclusions

The regulation of motors is characterized by ensuring the evolution of performance reached over the past 13 years. Brazil has evolved from an inefficient technological level to levels of efficiency similar to those in developed countries. This regulation is remarkable for its big scope, and its innovative aspect of establishing a way for the continuous upgrading of performance standards by means of a Target Program.

The efficiency levels proposed by the Target Program are already achieved by the current high efficient motor line which makes its mass production less difficult for the national manufacturers. It is expected that the market absorbs cost increases. The user will gain the increase in terms of energy consumption reduction and the OEMs will have less impact as the motor is only part of the total machine cost.

When the Target Program goes into effect, it will cause a significant reduction of electric energy consumption. The expected energy savings are remarkable as it means around 0.5% of total national energy consumption. It could be more if the efficiency of Brazilian standard motors didn’t have increased so much in the last 13 years.

The enactment of Target Program is already late. It is estimated to happen in the end of this year.

5 Acknowledgements

The authors would like to thank the Technical Group of Motors from the Labeling Program - PBE, who contributed to the accomplishment of this work, as well as Gustavo José Kuster, Marina G. Assumpção e Martiniano Muniz, former members of the Technical Committee of Motors for their professionalism and competence.

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Pump Systems I
The Activities of the German Pump and Compressed Air System Industry in the Field of Energy Efficient Systems

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Abstract
The German Pumps and Compressed Air Systems industry has a leading function for energy efficiency in the industrial use of motor driven systems.
The Compressed Air industry was a major partner of the successful “Druckluft-effizient” Campaign in 2001 – 2004.
Based on this success and experience the Pumps + Systems and Compressors, Compressed Air and Vacuum Technologies associations are partners in the new System-efficiency campaign which is a German implementation of the European Motor Challenge Program. The paper presents this campaign, which is a private public partnership, together with the German Energy agency dena.
The campaign contains a tailored consulting concept which will be the basis to examine the energy consumption in existing pumping systems.
The paper will present the actual stage of the new campaign and an overview of other activities of the manufacturers organized in the VDMA Federation.

1 Introduction

1.1 VDMA – the German engineering industry
VDMA is the German Engineering association with about 3000 member companies. The association represents 80% of the engineering turnover made by German companies, this was an amount of 136.5 Billion Euro in 2004.

VDMA is organized in a network structure:

- 37 professional sector associations
- 8 cross-sectional depts.
- Berlin Office
- European Office Brussels
- Representative Offices in China and India
- Liaison Office Tokyo.
1.2 Two sectors – one responsibility

About 200 companies are members of the Pumps + Systems and the Compressors, Compressed Air and Vacuum Technology Associations. Their production volume is about 7.3 Billion Euro. The export quote varies between 75 and 90%.

Based on the fact that about 28%\(^1\) of the electricity used in the European Industry (based on figures of the EU15) are needed to drive pumps and compressors, both branches have been early partners in the European process of promoting energy efficiency.

But this engagement is not only motivated by an environmental responsibility. It is also driven by the knowledge, that improving the energy efficiency of our customer’s systems is improving their productiveness and competitiveness.

1.3 Our sectors – working in an unique network

Both sector associations are integral part of several larger bodies. This gives a large responsibility but also unique possibilities to our members.

1.3.1 The European sector committees – EUROPUMP and PNEUROP

PNEUROP and EUROPUMP were deeply involved in the development of the original MOTOR CHALLENGE PROGRAM and are constructive partners for the European commission in all questions of energy efficiency.

EUROPUMP

EUROPUMP, or as its present full name defines it: Association Européenne des Constructeurs de Pompes, counts today 18 members being the national associations of pump manufacturers, in some countries also sales companies, in just as many European countries. The member associations represent more than 450 enterprises with a collective annual production worth about 8.2 billion Euro.

EUROPUMP’s central body is the council. The council members - company presidents, managing directors and other CEO's - are elected delegates of their national associations. The President is the head of the Council, the work of which is administrated by the General Secretary and his staff.

The commissions and their sub-groups are the bodies where the various issues dealt with by the Council are investigated, worked upon and prepared for decision by the Council.\(^2\)

\(^1\) „Compressed Air Systems in the European Union“ Peter Radgen, Edgar Blaustein 2000

\(^2\) www.EUROPUMP.org
PNEUROP

PNEUROP is the European committee of manufacturers of compressors, vacuum pumps, pneumatic tools and allied equipment, represented by their national associations.

PNEUROP speaks on behalf of its members in European and international forums regarding the harmonization of technical, normative and legislative developments in the field of compressors, vacuum pumps, pneumatic tools and allied equipment.

PNEUROP technical publications such as noise test codes, safety recommendations, terminology and symbols, test procedures for measurement of dust emissions and acceptance rules for vacuum pumps, are widely used in and outside Europe. Many of them have served as the basis for ISO and CEN standards. PNEUROP in principal has the same structure than EUROPUMP.

1.3.2 Standardization

On behalf of the German standardization body DIN, VDMA services the standardization in the field of mechanical engineering. So our sectors are the national secretariats for standardization in the field of pumps and compressed air systems. They are representing Germany in all relevant international standardization committees, especially in CEN TC 197 and ISO TC 115 for Pumps, CEN TC 232 and ISO TC 118 for compressors and compressed air systems and ISO TC112 for vacuum pumps. More than that representatives of our association are involved in the standardization of other products via liaisons with the responsible Technical Committees. Those are established with e.g. TC's for Oil and Gas, Vibration and Noise, Waste Water and Water supply.

2 The Activities of the German Pump and Compressed Air System Industry in the Field of Energy Efficient Systems

2.1 History

In the early nineties of the last century – effected by the discussions about the implementation of the Kyoto Protocol and rising energy costs – our industry started to evaluate the worth of energy efficiency for it's customers. Even if several companies had done a lot of efforts before, the time was ripe for a common understanding of this issue.

This new understanding founds it's opposite in the user industry’s efforts to reduce purchase costs to a minimum without a wider calculation of consequential costs. Life-cycle cost thinking was a theoretical approach mostly used by scientists.

3 www.PNEUROP.org
2.2 Activities in the last years

2.2.1 SAVE studies
The manufacturers of compressors, compressed air treatment compressed air supply supported the study “Compressed air systems in the European union” in 2000. Most figures have been supplied by industry. The study was the basis for most of the following measures.

An extract of a EUROPUMP study, accomplished at the University of Darmstadt, dealing with attainable efficiencies for single stage pumps end suction pumps for clear cold water application was issued as an "European Guide to pump efficiency for single stage centrifugal pumps". The discussions around the content showed that a more comprehensive treatment of the energy saving issue has to be done. It appears that the limitation to the pump itself would not approximately cover the potential of energy saving.

2.2.2 MCP pilot phase
Both associations are endorsers of the European motor challenge program. The work of this program was supported by technical input on a European and promotion on a national level.

2.2.3 Pump life cycle cost guideline
As the discussion within the Save WG showed that another approach had to be established which should tap the whole potential in energy saving. Since the middle of the 90's the European Pump manufacturers were working on the life cycle cost subject. This was the first agreed attempt to analyze the energy/performance/reliability and cost relation of a pumping system. The paper was published in Europe and the US at the same time in 2002.

Within this document the philosophy of the LCC idea is described. Much more than this guidance is given for the specification of pump systems, methods for the analysis for existing systems. Further chapters are dealing with examples for LCC analysis' and effective procurement by applying the LCC philosophy. To enhance the information about the paper I should mention the number of 14 case studies which clearly show the saving of costs which in all cases is not less than the reduction in energy costs.

2.2.4 Project Druckluft-effizient as a first common measure
The compressor, compressed air and vacuum technology association was one of the initiators and partners of “Druckluft-effizient". This campaign was a four years project realized from 2001 to 2004. The institutions like the German energy agency dena, the Fraunhofer ISI which was the technical project leader and our association have been active together with 17 industrial partners:
The campaign – the organization and show cases were described a few times – was in the German compressed air market the real break through for a system-thinking. Even there are still a lot of systems operating on a poor level, the investors of larger new projects are asking for an energy efficient system design.

Results of Druckluft-effizient

- The companies involved improved their analyzing and reporting methods for compressed air system analysis.
- The competition between different design philosophies is an advantage for the improvement of the level in the market.
- The press – and not only the technical press – is now aware of industry’s competence in supporting the users in system efficiency questions.

2.3 Actual projects

2.3.1 Project “System efficiency in the industry”

Concept

The idea of the new campaign which is very close to the philosophy of the original EUROPEAN MOTOR CHALLENGE PROGRAM is to improve the system energy efficiency of motor driven systems by information, education and consulting for the user.
The concept offers the possibility to integrate activities for the three industrial fields:

- Pump systems
- Compressed air systems
- Ventilation systems.

End of 2004 the campaign started with the pump system module and there is the possibility to add on the two others in 2005.

**Partners**

The initiators of this project are the German Energy Agency dena and the VDMA associations pumps+systems and compressors, compressed air and vacuum technologies.

In May 2005 seven industry partners are actively involved in this project which are:

- Danfoss GmbH
- Deutsches Kupferinstitut e.V.
- Grundfos GmbH
- KSB AG
- M+W Zander Energie + Anlagen GmbH
- Sulzer Pumpen (Deutschland) GmbH
- Wilo AG.

**The consultancy modules**

In comparison with the former campaign Druckluft-efficient there is an evolution of the consultancy module. We have now a three-stage model as follows:

- Initial consultancy
  
  This is a one day inspection which gives the consultant an overview of the systems and of the energy management of the company. The result will be a report highlighting systems worth to evaluate in a next step and structural questions.

- Energy saving analysis
  
  The content of this stage is a real energy analysis covering one or more systems. This includes an understanding of the process and measurement in the system. Aim of this stage is a detailed report covering an action plan (technical measures) to improve the energy efficiency of existing pumping systems and calculation of the payback period.

- Implementation consultancy
  
  This is a new approach trying to overcome the classical barriers for investment in energy efficiency. This covers explicit economical questions as financing and split budgets and technical items as distrust against new solutions. Possibly this consultancy will lead us to a toolkit usable for the partners and later on for the whole industry.
The consultancy module has been developed together with the partners of the campaign. The result is a Guideline for all consultants responsible for the different stages. This is the basis for a neutral communication to interested pump users willing to improve their existing pumping systems.

The synergies between the motor driven systems

From Druckluft-effizient and from our experiences with sector efforts in the last years we have learned some facts

- Most companies interested in the improvement of the energy efficiency do have one responsible person for all systems.
- If a company was successful in optimizing one system, it will have a look on others
- The management in larger companies than in SMEs is not interested in a single system as a compressed air installation. But it is interested in improving the energy costs and the competitiveness.

The aim is to offer the user the whole range of information to optimize his performance. But if the manufacturing industry is involved, the user gets information on a higher level as energy service companies can provide.

2.4 An optimal surrounding for the improvement of motor driven systems

2.4.1 Economic

Energy efficiency is not a blue sky event. It is a possibility for the users to improve there performance and competitiveness, so there is no argument to wait for investment for better economical surrounding.

Another question is the energy cost situation. A few years ago the relation between higher energy prices and the interest in energy efficient systems was theoretical, now it is reality. I won’t judge this because higher energy prices are in general an industry problem, but let us notice the fact as it is.

2.4.2 Legislation

Integrated product policy, Eco-design for energy using products, end-use efficiency and energy services, integrated pollution prevention and control, Intelligent Energy – Europe and SAVE. Even if industry supports the target of reducing greenhouse gases and even if we see the possibility to create business with energy efficient systems, we have to state very clear, that the legislation in the energy field is too inhomogeneous and inconsistent. The current situation with different political initiatives – on national and European level – is confusing the industry. Manufacturers and users!
Let me try to explain it by an example of the Eco-design directive. As a merger of several legislation projects it became a product related framework directive. As a product related legislation this directive is an effective tool and we are investing in this directive a lot of manpower since more than three years. But it is still not foreseeable which products will become subject of an implementing measure.

It seems that the framework directive is focused on serial consumer goods, but also industrial pumps, compressors and fans are in the scope and it is possible – here is the need of further evaluation – that they fulfill the Article 12 requirements. But if there would be the project of implementing measures for this products, industry will loose a lot of capacities used today for developing and promoting the system approach for which we await a higher energy saving potential.

3 Conclusion

For pump and compressed air systems, there is a potential for energy savings up to 30%. We only can enter this potential if we consider the whole system but not only the product or the component. Scientific literature is available in a very good way but we now have to start or to continue the market transformation. Successful examples are known. The users need consultancy by their suppliers according to the selection of energy efficient pump and compressor systems in case of building up of new plants or renovation of old ones. This is the best way to improve the productivity and competitiveness for the users of pump and compressor systems.
The Development of a North American Pump System Initiative: An Exploration of Opportunities and Strategies for Market Transformation


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Abstract

Pump systems are a significant opportunity for energy efficiency improvements. A number of different programmatic approaches have been tried in the United States with somewhat mixed results. ACEEE was retained by the Hydraulic Institute to explore possible opportunities for an industry-developed market transformation initiative. The work involved a review of past pump system and market transformation initiatives, and exploration of possible initiative formats that would benefit the market while creating business opportunities for pump manufacturers and service providers. This paper summarizes the findings, provides updates on current initiatives, and offers insights into how pump system market transformation initiatives can be constructed.

1 Introduction

Pump systems have long been recognized as a large opportunity for energy efficiency improvements, but success in deploying initiatives has been mixed. With increasing energy prices and competitive pressures, interest has increased in developing a national pump system initiative. The American Council for an Energy-Efficient Economy (ACEEE) undertook an assessment of markets and potential initiative strategies to advise the pump industry association, the Hydraulic Institute (HI), in developing an initiative. This paper summarizes the key findings and provides an update on the status of the HI’s Pump Systems Matter (PSM) initiative.

1.1 Motor and Pump Energy in the United States

Nationally, motor systems account for 50–60% of electricity used in the United States. Nearly half of this use is in the industrial sector, with the rest distributed among the residential, commercial, and utility sectors. In the industrial sector, about two-thirds of the electricity use is for motors (Nadel et al. 2002). Pump systems account for about 25% of industrial motor system energy use, or about 11 percent of all industrial electricity use. The other important pump markets are the water/wastewater industry (where pumps account for 46% of the motor energy), agricultural irrigation (where almost all of the motor energy is used by pumps), and heating and cooling of commercial and institutional buildings (where pumps account for 2% of total building electricity use). Combined, these represent over 112 billion kWh of electricity use annually (Elliott and Nadel 2003).
While some opportunities exist for more efficient system components (e.g., pumps), the greatest electricity savings in pump systems come largely from optimization of the system itself (Elliott and Nadel 2003). As a result, the costs and savings resulting from a project are site specific, reflecting the unique opportunities available at the site and the engineering and equipment expenditures required. In addition, the energy savings reflects only a portion of the benefits to the end-user, with the benefits from increased reliability, increased productivity, and reduced maintenance frequently exceeding the energy savings. Thus, if a national pump system initiative is to achieve significant energy savings, it must address the practices in the market, recognizing the non-energy benefits from these changes rather than focusing solely on the efficiency of components. One strategy for achieving this goal is market transformation.

1.2 Overview of Market Transformation

Market transformation means reducing, in a sustained manner, market barriers to the adoption of cost-effective energy efficiency products and services. Market transformation initiatives attempt to make structural changes in a market such that the “desired” products, services, and processes (e.g., greater energy efficiency) permanently penetrate the market. The goal of market transformation process as applied to the motor system market is to accelerate the movement of the market from a component focus (the existing market) to a system focus (the transformed market). If the most important and relevant market barriers have been addressed to the point where efficient goods and services are normal practice in appropriate applications, and these changes are sustained over time, then a market is transformed.

Due to the substantial effort required, a market transformation strategy for a particular product or service is generally designed to promote comprehensive changes across many parts of a market, not just at the margins. For the markets chosen, substantial increases in the share of the desired products, services, or processes appear achievable. By choosing measures in this way, savings can be maximized while making efficient use of limited resources. The real benefits of market transformation are achieved when multiple activities are combined into coordinated initiatives.

Market transformation efforts are different from most traditional utility demand-side management (DSM) programs in several respects. The primary difference is that the fundamental goal of market transformation is to change markets, not save energy in the short term. By changing markets, market transformation initiatives are designed to save substantial amounts of energy in the long term. As a result, market transformation activities are devised in direct response to existing market conditions and identified market barriers.

Understanding the particular market barriers to widespread adoption of a technology or service is essential for developing and implementing successful market transformation activities. In addition, market transformation initiatives generally are broader and longer term than conventional DSM programs. A market transformation initiative may have several phases, many players, and a variety of activities. Coordination among the rele-
vant players is thus necessary to ensure that a market transformation initiative or strategy is effective and the broad goals are accomplished.

Since the primary goal of market transformation is to change markets, the evaluation of market transformation programs emphasizes progress made in addressing market barriers and not precise measurements of program energy savings. While many traditional DSM programs include some of these attributes, few include all of the attributes that typify market transformation programs. However, market transformation is not a label that uniquely identifies certain energy efficiency program designs to the exclusion of others. It is instead an objective that all energy efficiency programs have at least a theoretical potential to achieve, although some programs are clearly more effective at achieving this objective than others.

Market transformation initiatives typically include activities designed to accelerate the market adoption of a particular energy-saving measure so that it becomes (and hopefully remains) common practice much sooner than it would otherwise. Accordingly, market transformation initiatives often include activities designed to: (1) stimulate the development and market introduction of new energy-efficient models or business practices; (2) strategically build the market share of these new products and services until they attain a niche position in the market; and then (3) change consumer purchasing practices in order to further expand the market adoption of these products and services so that they reach mass-market status and eventually become common practice. Figure 1 presents a schematic representation of the general phases of the market transformation process.

![Figure 1: Phases of a Typical Market Transformation Process](image-url)
Different activities or “tools” are appropriate at different points along this market diffusion curve since barriers are often a function of product/market maturity. For example, research and development, and technology procurement efforts may be employed in the early stages of an initiative in order to stimulate the introduction of new high-efficiency measures. Rebates and targeted outreach to large purchasers (e.g., bulk purchases) may be used to increase strategically market penetration until the measure achieves “niche” status. Consumer education, loans/rebates, and other promotional activities such as United States Environmental Protection Agency Energy STAR\(^1\) or National Electrical Manufacturers’ Association NEMA Premium\(^{TM}\)\(^2\) labeling may be used to expand a measure’s market share to its full mass-market potential.

2 Elements of a Market Transformation Initiative

Drawing from this experience, in general terms, a market transformation initiative or strategy for a specific market segment or end-use will often involve:

A careful analysis of the overall market, including identifying the particular barriers that are hindering the development, introduction, purchase, and use of the targeted measure. For example, in the early 1990s a B.C. Hydro energy-efficient motor initiative was undertaken to move the motor market to energy-efficient product. As a result of a study of the motor market, special attention was devoted to improving local availability and reducing the initial cost of energy-efficient motors, concentrating initially on large customers and large motor distributors who were identified as key market actors. The U.S. Department of Energy Industrial Technology Program has funded similar studies for other sectors (e.g., United States Industrial Electric Motor Systems Market Opportunities Assessment [Xenergy 1998] and Assessment of the Market Potential for Compressed Air Efficiency Services [Xenergy 2001]). Such a study can also include collection of baseline market data necessary for future evaluation.

A clear statement of the overall goal of the initiative or strategy as well as the specific objectives that will be accomplished along the way by the different initiative activities. In the case of the B.C. initiative, the strategy was to raise the local market share in order to make provincial, and ultimately federal, minimum-efficiency standards uncontroversial (Nadel et al. 2002). Measurable objectives should be established to track initiative performance.

The development of a set of coordinated activities that will achieve the desired objectives and systematically address each of the identified barriers. In the B.C. Hydro example, the initiative included education and incentives for vendors and customers. Among the activities that a pump initiative might include are expanding on HI’s existing training and tools in cooperation with HI’s members and other interested parties, or developing performance standards and design guidelines for pump systems.

\(^1\) http://www.energystar.gov/

\(^2\) http://www.nema.org/gov/energy/efficiency/premium/
Successful implementation of the individual activities, including periodic evaluations and adjustments designed to respond to actual experience. In the B.C. Hydro example, as a result of evaluation results, program operators decided to adjust incentives for energy-efficient motors downward several times.

Development and execution of a plan for transitioning from extensive market intervention activities toward a largely self-sustaining market (i.e., an “exit strategy”). In the B.C. Hydro example, the exit strategy was minimum-efficiency standards; for other market transformation initiatives, other strategies may be employed. However, B.C. Hydro’s “exit” applies only to sales of efficient motors in new construction and replacement situations; promotion is still needed for sales in retrofit situations and for sales of even higher efficiency “premium-efficiency” motors in new construction and replacement situations.

3 Past Motor and Pump System Initiative Experiences

While the potential for motor system efficiency has long been acknowledged in the engineering community, attempts to design energy efficiency programs to capture this potential only date back just over a decade. To date, these programs have struggled to balance the needs for site-specific engineering services with program costs, though interest remains high among mature industrial programs in developing program strategies (Elliott and Nadel 2003). On the other hand, we have a record of successful energy-efficient motor and compressed air programs and initiatives to draw upon (Nadel et al. 2002).

Programs focusing on fan and pump systems began around 1990, starting in Canada but then progressing to several regions of the United States. Early programs were offered by B.C. Hydro and Ontario Hydro and focused on identifying good applications for adjustable speed drives. However, this focus proposed an answer before asking which technologies make the most sense for each customer. By 1993, the Canadian utilities began several pilot projects that used a systems approach to optimize the entire motor-driven system. Due to a shift in utility priorities, these programs were discontinued before they moved out of the pilot stage but many of the people working on these programs participated in the development of a Performance Optimization Service (POS) in Wisconsin (Nadel et al. 2002).

The Energy Center of Wisconsin’s POS operated in the mid-1990s. Under the POS program, utility customer service representatives identified candidates for POS services, and engineers were hired to provide customers with quick, free engineering "walk-through" analyses of their systems. If substantial savings were projected, engineers prepared feasibility study proposals, collected system-load and operating data, and prepared feasibility study reports that recommended design strategies. To meet the need for specialized engineering skills, the program trained engineers in system optimization. The POS program provided initial audits to 36 sites and detailed feasibility studies to 11 sites (Bensch 1999). Ultimately, however, only six customers decided to implement projects; most of the others never made a decision. As a result of this low
implementation rate, as well as the high cost of marketing and engineering, the Energy Center decided to cancel the program. Program staff felt that the concept had a lot of merit, but more work was needed to streamline procedures and improve marketing so that costs could be kept in check while participants’ roles were increased (Meadows 2000). Based on these experiences, several groups began to explore modifications of the system optimization program model that addressed the shortcomings of previous programs. One approach was a tiered screening model developed by Flow Care Engineering for Ontario Hydro (see Figure 2) that is intended to insure that resources are efficiently applied to the opportunities with the greatest likelihood of success (Elliott and Nadel 2003). Unfortunately, as a result of utility restructuring, Ontario Hydro abandoned most of its energy efficiency programs before this model could be deployed.

![Figure 2: F&P Optimization Candidate Screening (Source: Martin 2001)](image)

### 3.1 Lessons Learned from Past Efforts

The experiences of the past almost two decades in both pump systems and market transformation have taught us some important lessons. In the area of pump systems, we now understand that a component approach to transforming that market is not appropriate. The application, not the product, determines the efficiency of the system. In addition, the non-energy benefits from optimizing the pump system, which are often greater than the energy savings, are likely to be the key factor in whether the customer chooses to undertake the project. We have also learned that opportunity identification is a resource-intensive activity; that it requires specialized expertise, skills, and tools to undertake it efficiently; and that a one-off approach to working with customers is unlikely to be cost-effective and sustainable as a strategy.
On the side of market transformation, we now understand that the most effective initiatives have a clearly articulated goal that can be embraced by a broad array of stakeholders. The activities need to be focused on addressing some clear market imperfections and ensuring that (1) metrics for success are identified early in the process and (2) collection of baseline data is a part of the initial planning. Choosing elements of an initiative depends upon the needs and capabilities of the participants and the shortcomings present in the current market. In many ways, the connections and contacts that an initiative undertakes may be more important in transforming a market than the specific activities. Experience tells us that with market transformation, there is no single model that works best. The structure and status of the market, the real (or perceived) market failures and opportunities, the relationships among the various market players, and their individual goals will dictate what structure is most appropriate.

4 Possible Initiative Structures

Based on ACEEE’s review of previous MT and motor system efforts, a pump system initiative could undertake a broad range of possible activities. Among possible elements of a pump system initiative could be:

- **Tools** (e.g., case studies, computer models, or fact sheets) to assist in design, evaluation, and equipment selection for an optimized system
- **Training** to increase understanding of pump system optimization among a range of target audiences of end-users, specifies, systems designers, and distributors
- **Voluntary standards** that define best practices for design and evaluation of pump systems
- **Certification** of pump system optimization specialists so that the market can identify qualified experts
- **Awareness and education activities** (e.g., case studies, articles, workshops, and even paid advertising) to increase understanding of the importance of optimization to pump system energy use and also to provide information on where to seek help
- **Branding** of the initiative to aid in building awareness
- **Technical assistance** to end-users and the design community to improve their designs and increase awareness of the importance of pump system optimization
- **Financial incentives** to encourage evaluation of system optimization to build awareness and demand for optimization services

Because of HI’s current strength in tools, training, and standards, ACEEE recommended that the national initiative build upon these activities, which could be complemented by some national awareness elements such as case studies and articles. These elements could evolve to include a certification element, which would build upon the others.
The technical assistance and financial assistance elements would be better included in state or regional programs that build upon the national initiative. These elements need to be tailored to the needs of local markets, and it will be easier to secure the funding at the local level through existing energy efficiency programs.

5 Status of U.S. National Pump System Initiative

In part based on the research and recommendations from ACEEE, HI announced its national pump systems educational initiative called Pump Systems Matter™ (PSM) in September 2004 (HI 2005). HI made its first public presentation on the initiative in April 2005 (Taylor 2005), identifying lack of market awareness and knowledge as the key barriers to improved pump system efficiency. The initiative’s goals are:

1. Transforming the owner/operator and contractor from focusing on lowest first cost to total lifecycle cost
2. Developing new educational materials, tools, and awareness
3. Changing the owner/operator and contractor from buying cheap to buying “right”

As ACEEE suggested, PSM will initially build upon the existing intellectual content that has been developed by HI, including HI/ISO standards, pump system training materials, and other technical materials. The initiative will spend the summer of 2005 establishing its governance and developing a multi-year work plan to be launched in the fall. One of the key initial tasks will be to undertake a pump system market assessment to confirm the preliminary assessment by ACEEE of target market markets. Part of this activity will be to plan for measurement of the success of the initiative through the identification of key market “metrics” that can be used to evaluate the success of the initiative and also to develop baseline values for these metrics.

The initiative will work with state and regional market transformation efforts to leverage existing energy efficiency programs in reaching end-users. The initiative intends to provide a kit of tools, training, and technical materials that can be used by local programs to support their deployment. In particular, PSM would support the use of the Pump System Assessment Tool (PSAT) system evaluation program with training, certification of Qualified PSAT Specialists, and technical support. This tool provides consistent and reliable evaluation of pump systems. In addition, by involving energy efficiency market transformation programs in the initiative, the HI can better tailor future initiative offers to meet the needs of market transformation programs while sharing the cost of developing and deploying awareness and educational activities, which can most effectively be deployed at a national level.

The initiative also plans to work with the engineering and pump distribution channels to build supply-side support for pump system optimization. Among these activities will be promoting the awareness of the benefits to customers from a systems approach while

3 Information on the PSAT program developed by the U.S. Department of Energy can be found at http://www.oit.doe.gov/bestpractices/software_tools.shtml#psat.
also creating value-added opportunities for the supply channel (e.g., distributors or engineering consultants). Among the elements targeted at the supply channel are the system training and Qualified PSAT Specialist activities. By insuring that both the supply channel and the energy efficiency market transformation programs are delivering a common and consistent message, the goal of changing market behaviour from a first-cost to a life-cycle focus can be more effectively achieved.

6 Discussion and Conclusions

The development of a national pump system initiative based on a market transformation model offers significant opportunity for success. By looking at the successful (and not so successful) experiences of the past two decades with industrial energy efficiency programs, market transformation efforts, and motor systems programs, we now have a good understanding of how to structure pump systems efforts to maximize success. The pump industry is in a period of flux, moving from a commodity-centered model to a value-added model where services become the focus. This transition creates a unique opportunity to transform the market. The leaders of a number of the key U.S. pump manufacturers understand the importance of making this transformation and have begun to restructure their own organizations to reflect this anticipated, new market reality. Together with their strong association, HI, this creates a strong foundation that an initiative can be built on.

Perhaps the most interesting aspect of the PSM so far has been that the motivation for establishing the initiative came from within the industry and that it has continued to lead the development efforts. The success of past MT efforts have hinged upon the supply channel seeing value from the efforts, usually in the form of market differentiation. With PSM, we see industry driving the process and beginning to restructure their companies in anticipation of the transformation.

While the PSM initiative still faces significant challenges before it can be called a success, it has been built upon the best knowledge and experience available, so should provide a true test of how market transformation can be applied to complex systems. Unfortunately, we won’t be able to make that assessment for a number of years. We hope that by incorporating a market baseline and evaluation effort early on we will get a clear answer.
7 References


Getting it Right, Applying a Systems Approach to Variable Speed Pumping

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Abstract

It is fairly common that variable speed pumping is misunderstood and that variable speed drives are at times applied in situations where they should not be used. This paper gives a review of proper and improper use of variable speed drives and explains how the operating point of the pump and hence the possible energy savings depend on system parameters not connected to the pump, but the system.

A review of the concept of specific energy for a pump system, the cost of pumping as a function of speed, static head, motor-, pump-, drive-efficiencies and the duration curve is made. It is shown how a systems approach has to be used in order to achieve the best possible result from an energy point of view.

The paper compares energy uses for different control methods such as on-off regulation, throttling, and by using variable speed drives.

The presentation includes examples of a good and a bad application for variable speed drives.

1 Introduction

Many times, variable speed pumping can save a tremendous amount of energy and sometimes actually increase the energy consumption. It is therefore important to understand when to use them and when not to use them.

A common reason for using variable speed drives (VSDs) is to correct for over-sizing. That most pump systems are oversized should not be a surprise to anyone. Accurately calculating the required head and rate of flow to be delivered by pumps is difficult. Safety margins are therefore usually added during the design phase. In addition, flow resistance often increases with time and flow requirements often are set to accommodate possible future increases. When all of these factors are considered, it is easy to understand why most systems are oversized and capable of providing more flow than needed.

A systems approach to evaluating pumping systems starts at the process demand. When a system is designed, many different solutions will usually be able to fulfill the process demands. The task of the designer will then be to choose the most cost effective of these solutions. This paper will discuss some tools and methods that can be used when comparing different system solutions.
2 System Flow Demand/Variations

There are a number of alternative solutions, such as throttling, speed regulation or bypass control, which can be used to control the rate of flow.

The process demands will generally dictate the type of control system needed. For example: Do the system rate of flow/head requirements change with time? Is it necessary to be able to accurately control the rate of flow? Are the changes in flow requirements continuously variable and spread over a relatively broad range, or at a few discrete flow rates? How large is the desired rate of flow and how does it vary in time? The answer to these questions will give guidance to the design of the system and also to the size and maybe numbers of pumps that have to be used. It may seem like the above questions are obvious. However, it is surprising how often these issues are overlooked.

The flow demand in a system and its variation in time can easily be presented using a duration curve, which shows how many hours a certain rate of flow is exceeded. The highest demand will thus be shown to the far left in the diagram. See Figure 1.

![Flow Duration Curve Diagram](image)

**Figure 1:** Example flow duration curves

Examples of duration curves for three different systems are shown. The total flow required (i.e., the area under each curve) is the same for the three systems, but the distribution is obviously quite different. This type of curve is a good starting point for overall system analysis.

Further consideration, such as the relationship between system flow and head requirements, is needed to fully understand system requirements and optimize design. But even a casual review of the three duration curves shown in Figure 1 reveals that the kind of pumping configuration that is suitable for System A (a single-size pump, selected to operate efficiently at the constant flow requirement) would be less than optimal for either System B or C.
3 Flow Control

The two basic methods for flow control are to change 1) the system curve by throttling, or 2) the pump curve, by using a VSD. The most common option is to use a throttling valve. VSDs are almost always more efficient than throttling valves, and they will usually be more economical to use than valve regulation, especially on a life cycle cost comparison. Controlling rate of flow by by-passing some of the pumped liquid is also used in many applications, in spite of its being uneconomical.

In systems where precise control is not needed, other solutions besides throttling valves or VSDs, may prove to be more efficient. For example, properly sized pumps running on-off can be a very efficient solution in many systems.

3.1 Flow Regulation by Throttling

When the flow is regulated using a throttling valve, the system curve is changed. The duty point moves to the left on the pump curve, (see Figure 2) when the flow is throttled. The vertical lines in Figure 2 represent the throttling loss in the valve.

![Figure 2: Throttling a valve changes the flow rate by adding pressure drop in the valve. The operating point moves along the pump curve.](image)

The specific energy ($E_s$), as discussed in section 4.1, can be calculated for each such operating point by dividing the input power to the motor by the flow rate. $E_s$ usually increases rapidly as the flow is reduced.
3.2 Flow Regulation by Using Variable Speed Drives

Figure 3: With a VSD, the operating point moves along the system curve. The graphs show two different system curves, one with and one without static head.

Figure 3 shows two system curves and reduced pump curves (solid lines), along with lines of constant efficiency (dashed lines), the middle one having the highest efficiency. The curves demonstrate what happens in a speed-regulated system. New pump curves are obtained as the speed is decreased. New operating points will be determined by the intersection of the system curve and a reduced pump curve. It is important to separate systems with static head from systems without static head, since they react quite differently to speed changes. In a system with static head the pump efficiency will change as the speed is changed, see the left part of Figure 3.

A variable speed drive makes it possible to adjust the output to the demand without throttling. The impact of an oversized pump can therefore often be neutralized, resulting in significant energy and cost savings. In the case of systems exhibiting a large amount of static head, however, special care has to be taken. When the speed is reduced in such a system the operating point moves higher and higher on the reduced pump curves, until the pump finally is dead-headed. It should be stressed that long before that happens, the pump leaves the preferred operating range and can experience severe damage if operated under such conditions for an extended period of time. It is therefore necessary to take a broad view of the system before deciding on what kind of control to use.

In systems without static head, however, the new operating points obtained when the speed is reduced will remain at the original efficiency as shown on the right side of Figure 3.

Variable speed drives will give good control of the flow rate except when the static head is high and the pump curve has a flat upper portion. In those situations very small changes in speed can result in very large changes in the rate of flow.
VSDs generally greatly reduce the operating cost in systems when compared to throttling valves, and in systems with little or no static head without throttling valves. In systems with high relative static head, extra care has to be taken when using variable speed drives to avoid the pitfalls of low pumping efficiency and operation in harmful flow regimes. The allowable speed range thus becomes restricted both from an operational and economical point of view. A common mistake is to use the affinity laws to calculate savings using variable speed systems. These laws cannot be used to calculate new operating points, and hence energy usage, when static head is present in the system.

### 3.3 Drive Efficiency

Of course, like any other active component, the drive efficiency is not 100%. Figure 4 shows motor, drive, and combined efficiency for a modern pulse width modulated drive (the most common type of drive) operated at rated speed conditions (on a two-pole, 37.5 kW motor) (see Casada, et al. 1998). The motor efficiency alone, when driven directly from the power supply (i.e., without the drive) is also shown for comparison. As can be seen, the drive efficiency is in the upper 90-percent range. The drive also causes the motor to operate at a slightly lower efficiency than when the motor is driven directly across the line. Figure 5 shows the same motor efficiency curve as Figure 4, but for the combined drive and motor curve, and uses data that represent the torque variation of a typical centrifugal load.

![Efficiency Graphs](image-url)

**Figure 4:** Motor and adjustable speed drive efficiencies at rated speed (See Casada, et al. 1998)

**Figure 5:** Motor (rated speed) and adjustable speed drive (centrifugal-type load speeds) efficiencies (see Casada, et al. 1998)
However, simply considering efficiency alone doesn’t capture the essence of variable speed drives. The real saving derives from the drop in power that accompanies speed reduction. Figure 6 contrasts the difference in shaft power between fixed and variable speed in a system without static head, where the shaft power is approximately proportional to the cube of the speed.

Figure 6: Shaft power requirements for a fixed and variable speed driven pump (See Casada, et al. 1998)

4 Calculating Energy Use

4.1 Specific Energy

When comparing different solutions for a pump system it is helpful to be able to easily identify the system effectiveness and to compare different solutions. A useful entity for this comparison is the specific energy:

\[
\frac{\text{Energy used}}{\text{Pumped Volume}} = \text{Specific Energy} \tag{1}
\]

\[
E_s = \frac{P_{in} \cdot \text{Time}}{V} = \frac{P_{in}}{Q} \tag{2}
\]

\(P_{in}\) = input power to the driver

In systems without static head, this is rather straightforward using the equations above. In systems with static head the energy usage can be calculated the following way. The head needed from the pump can be separated into static and dynamic (friction losses). Substituting \(H_s+H_f\) for the total head in the expression for specific energy will generate the following expressions:
The "Hydraulic System factor", $f_{HS}$, indicates the relative amount of static head in the system. $E_s$ now has a minimum value: $H_s \cdot \rho \cdot g$, which would occur if all efficiencies were equal to 100% and there were no friction losses. If there is no variable speed drive in the system, then $\eta_{drive}$ is $= 1$. The different factors are all functions of the flow rate and will vary with the duty point. If a variable speed drive is used, they will vary with speed as the duty point moves along the system curve.

Motor efficiency will generally slightly decrease as the speed is lowered and the motor goes below 50% of full load. The drop in combined motor – drive efficiency can be substantial if the motor load drops below 30% of full load. The denominator: $\eta_{drive} \cdot \eta_{motor} \cdot \eta_{pump}$, $f_{HS}$ can also be seen as the overall efficiency $\eta_{gr}$.

The Hydraulic System factor will increase when the friction losses go towards zero, which happens when the duty point approaches the shut off head. The specific energy will always increase drastically as the duty point moves towards shut off head in systems with static head due to reduced pump, motor and drive efficiencies. In systems with high static head, this can happen even at a relatively moderate decrease in speed. In such systems, the area of usefulness of a variable speed drive can be somewhat improved by making sure that the system curve and the full speed pump curve intersect to the right of the pump’s best efficiency point.

As illustrated in Figure 7, the savings potential is very large in systems with low static head, whereas care has to be taken in high static head situations. When the speed is low enough to cause the pump to operate at, or close to, shut-off head, the specific energy goes towards infinity. When operating below the horizontal line D, energy savings will be realized compared to on-off operation.
4.2 Comparing Throttling and Variable Speed Drives

In a throttled system, the specific energy will increase rapidly as the flow is decreased. The specific energy for a speed regulated pump system can be higher than for an on-off regulated system, but will usually be lower and save energy compared to a throttled system. It has to be remembered though, that the ability to continuously regulate the flow is a common demand in many industrial applications and on-off regulation therefore is not always an alternative.

5 Examples

5.1 Incorrect Application of a Variable Speed Drive

A U.S. municipality uses multiple deep wells for their potable water supply. One of their deep wells installed in 1997 is approximately 500 m deep and uses a 10 stage vertical turbine pump with a 450 kW submersible motor controlled by a variable speed drive.

A recent preliminary evaluation revealed that the pump was operated between 100% and 83% speed, varying flow from 238 m$^3$/hr to 103 m$^3$/hr. Based on discussions with operators, three average flow intervals were used to evaluate system efficiency. Flow, head and power were measured at each interval. The results are shown in Table 1.
Table 1: Data for Flow Intervals (Process Energy Services, LLC)

<table>
<thead>
<tr>
<th>Hours</th>
<th>Flow (m³/hr)</th>
<th>Head (m)</th>
<th>Pump Speed (%)</th>
<th>Power (kW)</th>
<th>Overall Eff. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1800</td>
<td>238</td>
<td>451</td>
<td>100</td>
<td>488</td>
<td>60</td>
</tr>
<tr>
<td>1500</td>
<td>191</td>
<td>442</td>
<td>92</td>
<td>441</td>
<td>52</td>
</tr>
<tr>
<td>1500</td>
<td>103</td>
<td>430</td>
<td>83</td>
<td>345</td>
<td>35</td>
</tr>
</tbody>
</table>

Figure 8: System Curve and Pump Performance at different speeds (Process Energy Services, LLC)

The pump system provides a total of 870 455 m³ of water annually. An overview of the pump, head curves and total system efficiency curves is shown in Figure 8. Consumption data were calculated as shown in Table 2.

Table 2: Total System kWh (Process Energy Services, LLC)

<table>
<thead>
<tr>
<th>Hours</th>
<th>Flow (m³/hr)</th>
<th>Power (kW)</th>
<th>Consumption (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1800</td>
<td>238</td>
<td>488</td>
<td>878 400</td>
</tr>
<tr>
<td>1500</td>
<td>191</td>
<td>441</td>
<td>661 500</td>
</tr>
<tr>
<td>1500</td>
<td>103</td>
<td>345</td>
<td>517 500</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td></td>
<td>2 057 400</td>
</tr>
</tbody>
</table>
At an average cost of $0.13/kWh, annual energy costs with the drive installed are approximately $267 000.

After a review of system operation, it was determined that the existing variable speed drive could be removed and replaced with a soft start motor control to reduce system energy costs. The new pump operating strategy would allow the pump to cycle on and off a limited number of times each day to satisfy system requirements.

Estimated energy savings from this modification is calculated as follows:
Operating the pump at full speed (after removing the variable speed drive) to provide the same flow annually (870 455 m³) can be calculated as follows, assuming a full speed motor efficiency of 87.6% and pump efficiency of 76%:

\[
kW = \frac{\text{Flow} \times \text{Total Head}}{367 \times \text{Total System Efficiency}}
\]

\[
kW = \frac{238 \times 451}{367 \times 0.66} = 444 \text{ kW}
\]

At a flow rate of 238 m³/hr, the pump would need to operate 3657 hours annually to satisfy flow requirements. This corresponds to 1 623 874 kWh/year or 211 103 USD in annual energy costs, saving approximately 57 000 USD.

5.2 A Better Application of a Variable Speed Drive

There are many examples of how variable speed drives have saved a tremendous amount of energy. A typical result from retrofitting pump systems with VSD units at the SINOPEC Yangtze Petrochemical Company in Jiangsu Province, China gave the following results: The project included installation of 34 VSDs on existing pump systems which were generally oversized with rates of flow controlled by throttling valves (see Jiangsu Energy Conservation Center 2005). After the project was completed, the specific energy consumption of the pumps was reduced from 8.016 kWh to 5.766 kWh per ton of crude oil. 6.26 million tons of crude oil was refined in 2003. The plant thus achieved electricity savings of 14.08 million kWh/a (with 11 270 tons of CO₂ emissions reduction), amounting to 6.62 million Yuan RMB (approx. 660 000 USD). The payback period of the project was 0.48 years.

6 Summary

To understand a pumping system it must be realized that all of its components are interdependent. Sub-optimization on the component level can easily be deceptive.

If the system curve exhibits substantial static head, problems with VSD applications can occur. VSDs generally reduce the operating cost in systems when compared to throttling valves, and in systems with little or no static head without throttling valves. In systems with high relative static head, extra care has to be taken when using variable speed drives to avoid the pitfalls of low pumping efficiency and operation in harmful flow regimes. The allowable speed range thus becomes restricted both from an operational and economical point of view.
7 References


Intelligent Pump Control Software within AC Drives Optimizes the Energy Efficiency of Parallel Running Pump Installation

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Abstract

Saving energy in parallel pump installations for tank filling/emptying is a complex task. Each pump in a parallel installation has an effect on each of the other pumps. Moreover, if the pumps are not alike, selecting the optimal running order and method is a challenging task using traditional means.

We have developed an intelligent package of control software for AC drives. Using this software, which ABB has made available for its industrial drives, interconnected AC drives can ensure the optimal pump operating arrangement in terms of pump efficiency at any operating point, without using an external programmable logic controller (PLC). Other energy-saving features include functions to prevent clogging up of pipelines and pumps in sewage treatment.

The paper at hand describes the features of the new software, and endeavours to explain how a pump user can improve the energy efficiency of pumping systems with it.

1 Introduction

In general, AC drives are the most energy-efficient way of controlling pumps. This paper describes how application specific software developed for AC drives can further boost energy efficiency in parallel running pump installations. This solution is particularly energy efficient in wastewater applications where liquid is pumped in or out from the storage tank. In these applications the liquid level in the tank is one of the controlled variables. When the liquid level of the tank rises, the pumps compensate these changes and pump more liquid out from the tank (emptying mode). When the level of liquid lowers the pumps run at a lower speed.

When dimensioning a wastewater pump station, it is quite common that the pumped volume varies a lot depending on the process, time of day, consumption, etc. To manage different volume requirements, one option is to have smaller pumps running in parallel. With a decreased flow demand a smaller pump is optimal. When the flow demand increases, more parallel pumps are switched on to meet the capacity requirements. Controlling only the level of the tank leads to a situation where energy saving optimization is only guaranteed through a right dimensioning of the pumps, motors and drives. With the solution described in this paper the primary controlled variable is energy efficiency and the secondary the level of the tank.
1.1 Efficiency of the pump, motor and drive

Total efficiency of the system depends on many factors. In general, the bigger the drive, motor or pump, the better the efficiency. When running the system at low speeds, the total efficiency also decreases. In the normal operating area of the pump, which is 35 to 50 Hz, the total efficiency of the system does not vary too much. Efficiency of the drive motor system at the nominal point is about 90%. With 35 Hz the efficiency is about 83% (Europump and Hydraulic Institute 2004). In general, the pump efficiency varies between 50 to 85%, depending on the speed of the pump and the system curve.

1.2 Affinity laws

Affinity laws in Table 1 show the proportion of speed (n), flow (Q), head (H) and power (P). Speed and flow are proportional. The power needed is proportional to the cube of the speed or flow. When operating the pump at the nominal point, the efficiency of the system is normally at its highest. Based on the affinity laws it is possible to optimize the energy efficiency if the speed of the pump is reduced, for example, by 10% from 50 Hz to 45 Hz. At the same time, the flow is 10% smaller, so the time needed to achieve the same total flow is 11% longer. The power needed is only 73% of the original. With this change 19% less energy is needed \((1-(0.73\times1.11))\). Total efficiency of the system stays within the same range, but the energy needed is reduced.

<table>
<thead>
<tr>
<th>Flow</th>
<th>Head</th>
<th>Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \frac{Q_1}{Q_2} = \frac{n_1}{n_2} )</td>
<td>( \frac{H_1}{H_2} = \left( \frac{n_1}{n_2} \right)^2 )</td>
<td>( \frac{P_1}{P_2} = \left( \frac{n_1}{n_2} \right)^3 )</td>
</tr>
</tbody>
</table>

Using this efficiency speed (45 Hz in this case) creates a 19% energy saving with a 10% smaller capacity. To keep efficiency speed as the primary control method and use nominal speed only when full capacity is needed, it is possible to achieve double-digit energy savings in the long run.

This approach is optimal in a system where the static head is low; this is a typical with wastewater pump stations. With a higher static head the energy saving potential is smaller.

1.3 Life cycle costs

To compare the different savings of the pump station it is useful to compare the life-cycle costs and not only the investment costs or system efficiency figures. These costs
can be split into three: initial costs, power consumption and maintenance. Figure 1 below shows an example of a life-cycle cost analysis.

![Life-cycle costs of a pump (Gylling 2005)](image)

Figure 1: Life-cycle costs of a pump (Gylling 2005)

## 2 Software solution

Intelligent Pump Control (IPC) is an optional software package for ABB low voltage AC industrial drives. Incorporating all the most common functions required by pump users, it eliminates the need for an external PLC and other additional components. A pump system with fewer electrical components is always more reliable, especially in a harsh environment typical in wastewater pump stations. IPC can help save energy, reduce downtime and prevent pump jamming and pipeline blocking.

All of the IPC features presented in this paper are new innovations. The development of a new software package was based on a long-established experience with pump and fan control software for ABB drives. The new features were partly developed and tested in co-operation with ABB’s global pump customers.

One of the control features of the IPC is Level Control mode (patent pending). It is typically used to control the filling or emptying of wastewater storage tanks. A drive controlled pump is operated at a favorable point in its efficiency curve to minimize energy consumption. Level control can be used with a single pump, or 2 to 3 pumps/drives in parallel.

### 2.1 Control logic of Level control mode

Control logic of the Level Control mode in emptying is described in Figure 2. The key issue is to run pumps with efficiency speed (45 Hz in Chapter 1.2. example) as far as possible. If the level of the tanks varies so that a higher pumping volume is needed, more pumps are switched on and run with efficiency speed. In this case there are three pumps. The start levels and efficiency speeds of the specific pumps are all user adjustable parameters to meet the specific requirements of the system. In a situation where
all pumps are running with efficiency speed, the level of the tank reaches the High 1 level (adjustable parameter), after this all the pumps start to run at a high speed.

With this approach, according to the calculated example in Chapter 1.2, it is possible to achieve almost 20% energy savings, and still have a flexible control method when the level of the tank and the pumped volume vary a lot.

![Control logic of the Level Control mode to run parallel pumps](image)

**Figure 2** Control logic of the Level Control mode to run parallel pumps

### 2.2 Other benefits with Intelligent Pump Control

Dimensioning a pump station with parallel pumps enables creating a redundant system. With the Level Control mode of the IPC, the redundancy of the system is 100%. If one of the pumps/motors/drives goes off, the system will continue uninterrupted. Even if the master of the parallel drives falls, it takes only 500 ms to have a new master drive. This is possible through a fibre optic connection between each drive. A 100%
redundancy of the system guarantees high usability and risk-free operation of the pump system even in fault situations.

The Anti-Jam function enables the drive to perform preventive maintenance on the pump. When the function is triggered, the pump is run at a high speed and then either reversed or stopped in a number of user-defined cleaning cycles. This helps to prevent congestion through build-up of particles. The trigger parameters are set by the user, with three different options available (high current, run-on time and external input). Safety parameters can be set to limit mechanical stress.

When operating with liquids containing particles there is always a risk that pipelines get stuck – especially when running with smooth control and/or slow speeds. With Level Control mode fast ramp in starting creates a flush effect which keeps the pipelines clear. If the pumps are running, they are always running close to the nominal point where the risk of pipeline problems is lower due to a higher flow. A special feature of the software seeks to prevent sediment build-up on the tank walls by randomly varying the surface level within a range preset by the user.

Pump Priority Control balances the operating time of all the pumps in the system over a long term. This facilitates maintenance planning and can boost energy efficiency by operating pumps closer to their best efficiency point. In a system where the consumption rate is higher during the day, for example, the drive can be programmed to operate higher capacity pumps during the daytime and smaller units at night.

3 Summary

Savings with the IPC software with parallel wastewater pumps can be divided into two: higher energy efficiency and usability benefits.

Having efficiency speed as the main control parameter for parallel wastewater pumps it is possible to achieve double digit savings in energy consumption. IPC software supports this approach. With the 45 Hz efficiency speed, a 19% energy saving is possible compared to nominal speed 50 Hz. As 85% of the pump lifetime costs are related to energy consumption, a potential saving with this approach is 16%, which is more than the investment and maintenance costs of the pump.

Usability benefits consist of many factors. A 100% redundancy keeps the system up and running even when one part of the system fails – no matter whether it is the master or follower in a parallel system. Other features of the IPC software such as the anti-jam function, flush effect and pump priority control guarantee trouble-free operation of a wastewater pump station.
4 Explanations

**Efficiency** – The ratio of useful energy delivered by a dynamic system to energy supplied to the system. In this paper efficiency means single efficiency of drive, motor or pump.

**Efficiency speed** – Energy efficient speed to run a pump in a wastewater pump station.

**Energy efficiency** – Energy consumption of the AC drive, motor and pump compared to the required flow.

**Fibre optics** – Thin fibre or plastics enclosed by a sheath and used in communications between the AC drives.

**Flush effect** – A sudden flow of water. In the IPC, start and stop ramps are short and the running speed is high enough to keep all particles in water moving. This is important in wastewater applications to prevent jam.

**High 1 level** – When the liquid in the tank rises up to this level, all pumps run with full speed. This is a parameter in the IPC.

**IPC** – Intelligent pump control software for the ABB industrial drive.

**Level control** – One control method in the Intelligent Pump Control (IPC) software designed for wastewater applications where the level of the storage tank is controlled.

**Redundant system** – A system where a failure of one part does not prevent the whole system from running.

**Start level** – When the liquid in the tank rises to this level defined by the IPC level control parameter, the pump starts to run with efficiency speed. This is a parameter in the IPC.

**Total efficiency** – Efficiency of the AC drive, motor and pump system.

5 References


Pump Systems II
Comparison of Variable Speed Drives and Control Valves for Flow Control in Pumping Systems

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Abstract

In the chemical industry, flow control with control valves (throttle control) is the most common method. Control valves are known to be relatively insusceptible to failure and relatively easy to select and configure. As pumps in plants normally do not only run in one operating point and due to the oversizing of the pump during the conception of the plant, the pump often does not run with maximum efficiency. So a part of the energy put into the system is always throttled by the valve. As an alternative to a throttle control, a variable speed device can be used to control the flow by controlling the speed of the pump. So the energy demand of the plant is decreased. In this paper, a comparison between throttle control and speed control is presented. One question of this examination is whether there are limits to either of the control types. Using speed control and regarding life-cycle-costs the principle economic aspects will be discussed.

1 Introduction and Definitions

At the Institute for Fluid Machinery and Fluid Mechanics at the University of Kaiserslautern a test rig to examine variable speed drives (speed control) and control valves for flow control (throttle control) in pumping systems is used. In the chemical industry throttle control is the most common method. Even though speed control often brings about some economic advantages, 80% of the plants in the German chemical industry are equipped with throttle control. The stress of competition on chemical industry is increasing. As the economic advantages can be calculated before building the plant, speed control will be found more often.

The aim of the project the test rig was built for was to find out, whether there are any limitations to the flow control of either of the control modes mentioned above. The plan of the test rig is shown below in figure 1. It is an open test rig. From the reservoir, shown at the right bottom of the figure, a piping system is leading towards the pump. On the suction side of the pump a temperature and a pressure metering point are mounted. The pump itself, shown at the left bottom of the figure, can be controlled by a frequency converter to adjust the speed or throttle control can be selected. Downstream the pump, another pressure metering point is mounted to calculate the head of the pump. Further downstream the pressure metering point is a junction for the bypass. The bypass is necessary for throttle control with zero flow rate. It is a standard part of industrial plants to prevent the rotating mechanical seal of the pump from overheating and getting damaged. The flow into the bypass can be adjusted by a manual valve and
is measured by an electromagnetic flowmeter. The bypass is leading back to the reservoir. Downstream the junction in the main piping system the flowmeter of the system is installed. It also is an electromagnetic flowmeter. Further downstream the flowmeter the control valve for throttle control is mounted. It can either be controlled by a PID-controller or operated manually. Upstream the pressure tank another valve is installed. It can be used to simulate different kinds of plants. The plant can be used as a plant with dynamic losses only or can be adjusted to a plant with a static head of 90 to 95% of the total head. An extract of the possible characteristic curves is shown in figure 2. The pressure tank is connected to a compressed air system by a compressed air regulator to keep the pressure in the tank constant without depending on the water level in the pressure tank. The pressure tank is equipped with a pressure relief valve to prevent the pressure from rising above the maximum allowed for the tank. A level indicator is connected to the tank and wired to a PID-controller. The PID-controller receives signals from the level indicator and controls the stroke of the valve being mounted downstream the pressure tank to keep the water level constant for the tests. From the valve the water is flowing back to the reservoir.

Figure 1: Plan of the test rig

For tests with throttle control the bypass was open. In industrial processes the bypass normally is open in a range of 2 to 5% of the nominal flow. This rule was also used for the test rig to keep the similarity to an industrial process. For adjusting the flow through the bypass the control valve was closed and the valve of the bypass was adjusted to 5% of the nominal flow. The settings of the valve have been kept like they have been adjusted for all the tests with throttle control. For the tests with speed control, the bypass was closed.
2 Flow control

2.1 Flow control valves

Control valves are devices to continuously vary the flow resistance of a piping system to throttle the flow. A control valve is made up of two functional units, the straight-way-valve and the PD-controller, operating the stroke of the valve. The most important parameter of a control valve is the $k_v$-value, describing the flow capacity of the control valve at standard conditions.

Figure 3 shows the diagram of flow control with control valves. In the diagram the specific energy $e$ over flow $Q$ is plotted. There are three different characteristic curves plotted: the characteristic curves of the plant, of the pump and of the efficiency of the pump. The point of intersection between the curves of the pump and the plant is the operating point. The characteristic curve of the pump is shown at constant speed. Three characteristic curves of the plant are plotted. The first one is the dotted curve with the lowest gradient, named “plant without control valve”, where $Q_{\text{max}}$ is realized. The curve drawn in a continuous line and named “control valve position “A”” is the curve of the plant with the control valve set for the flow at the point of the best efficiency of the pump. The third curve, dotted and named with “control valve position “B”” is the characteristic curve of the plant with the valve further closed to get smaller flow rates. The plant has a static head $e_{\text{stat}}$, which has to be overcome. The amount of energy being throttled is marked as $e_{SA}$ and $e_{SB}$ for the positions “A” and “B” of the valve.
2.2 Variable speed drives

In figure 4 the characteristic curves of the plant, the pump and the efficiency of the pump are plotted for speed control. The curves for the plant without control valve and for the efficiency of the pump are the same curves like in figure 3 for throttle control. The curve for the pump with $n_1 = \text{const}$ is the same, too. The curves for $n_2$ and $n_3$ are curves for the same pump with lower speed. The intersections between the lines mark the operating points. In contrast to throttle control with speed control, the area of the piping system remains unchanged. The change of the flow results from the new – lower or higher – speed of the pump. The efficiency of the pump is changing with the speed of the pump as well as with the load. The change in efficiency strongly depends on the type of plant, which means it depends on the part of the static head of the total head.
One huge problem in industrial processes is selecting the correct pump while planning the plant. It is necessary to know, which losses are caused by the components of the plant. Often it is not possible or very complex to calculate the losses exactly, so one method to prevent the pump from not reaching the necessary flow is to choose a pump which is too large for the plant. With this method the planner can be sure to get enough flow with the selected pump. The disadvantage of this planning-method is that the control valve is not fully open at the planned flow. But even with a correctly planned and chosen valve, the resistance of the piping system is higher than without the valve. This implies a permanent throttling of the flow. Shown in figure 2, is the difference between the curves “plant without control valve” and “control valve position “A””. This difference is named “e_{SA}”.

The amount of energy being throttled largely depends on the gradient of the characteristic curve of the plant. If the curve has a low gradient, the throttled energy is not very high. But if the gradient is very high, a large amount of energy has to be throttled, either because of the wrong sizing of the pump or because of changing the flow to partial load. The higher the gradient of the characteristic curve of the plant, the higher the amount of energy being throttled with the control valve. Another aspect concerning the possible energy savings is whether the plant has a static head or whether there are only dynamic losses within the plant. The plant in figure 2 has a static head. A high static head results in a small reduction of the speed of the pump, even if there is no
flow through the piping system. The higher the static head of the plant is, the smaller is
the reduction of the speed of the pump, and the lower is the potential for saving energy
with variable speed drives.

On the basis of the following figures 5 and 6, the chance of saving energy with variable
speed drives will be discussed. In figure 5 the diagrams for the specific energy $e$ as a
function of the flow $Q$ ($e,Q$) and for the power consumption $P$ as a function of the flow
$Q$ ($P,Q$) are plotted. The plant of figure 5 is a plant without static head. The only losses
are the dynamic losses of the piping system. Additionally the gradient of the character-
istic curve of the plant is relatively high. In contrast to this case, figure 6 shows the
characteristic curves for a plant with static head. The gradient of the characteristic
curve of the plant in figure 6 is very low. Compared with the static head of the plant, the
losses in the piping system are relatively small.

Figure 5: Comparison of energy consumption at a plant without static head

With speed control – in contrast to throttle control – the flow, the specific energy and
the power of the pump are functions of the speed of the pump. The flow $Q$ is propor-
tional to the speed $n$, the specific energy $e$ is proportional to the square of the speed $n^2$
and the power $P$ is proportional to the cube of the speed $n^3$.

On the left side of figure 5, throttle control is shown. Throttling the valve results in a
new characteristic curve of the plant, which is shown in dotted lines. Each working
point must lie on the characteristic curve of the pump as its speed remains the same
and with it the curve remains unchanged. The specific energy to be saved is marked
with arrows. On the right side of the figure, speed control is shown. In contrast to throt-
tle control, at speed control the resistance of the piping system only depends on the flow rate and with it the friction factor is constant. The new working point has to lie on one characteristic curve of the plant, while for each working point the speed of the pump is changed so that a new characteristic curve of the pump is the result. In the diagram about power on the right side, the amount of energy possible to save is marked with arrows. With a flow of $Q_{\text{max}}$, the necessary amount of energy is the same for both of the control types. The less flow is necessary, the more power can be saved. With the affinity laws for centrifugal pumps the power of the pump depends on the cube of the speed of the pump ($P \sim n^3$). This means that at 50% flow the necessary power is at $(0.5)^3=0.125=12.5\%$ of the power necessary for flow at the optimum working point. This example is shown in figure 5 with $e_{0.5}$. In this way, huge amounts of power can be saved.

But things are slightly different with plants with high static heads and very small dynamic losses in the system, as shown in figure 6. The gradient of the characteristic curve of the plant is very low, it nearly is a straight line. The minimum speed of the pump depends on the static head of the plant, as shown in figures 5 and 6. A comparison of the two figures for speed control shows the minimum speed of the pump for both cases. In the case of figure 6 there is still a reduction of the speed of the pump, but it is not as big as it was in the plant without static head. The reduction of the speed determines the saving of energy. If the reduction of speed is small, the saving will be small and if the reduction of speed is high, the saving of energy will be high.

Figure 6: Comparison of energy consumption at a plant with static head

Starting the discussion from these two kinds of plants, it is easy to see that there are plants, where speed control has economic advantages concerning energy over throttle
control and that there are plants, where throttle control is the more economic option. Because of the higher investments for a plant with speed control, it is necessary for economic reasons that the energy savings with speed control can pay back the higher investments. In figure 5 the plant is the perfect kind of plant for speed control. Even if the profile of the load for a typical day is not varying very much and if there are not many operating points in partial load, the amount of energy being saved usually is high enough to pay back the higher investments within less than three years. If the profile of the load for a typical day is more like a GAUSS distribution curve, a typical payback-time is less than one year. As the economic pressure in the chemical industry is still increasing, life cycle costs have to be discussed for each plant being built. Today, the economically most important thing while planning a plant is taking into account the life cycle costs but these are not limited to the investments.

As shown in figure 6, there are existing plants with a static head dominating the plant curve. If the dynamic losses of a system are very small, e.g. if the piping system has a larger diameter and the pressure to pump the fluid is very high, it makes no sense, as regards energy aspects, to invest into speed control. Comparing the possible savings in figures 5 and 6 (the arrows in the diagram about power for speed control) it is easy to see, that the maximum savings in figure 6 are much less than the minimum savings in figure 5. So in this case it might take 5 years or even longer for speed control to pay back the investment by energy costs.

So a close look at the costs of energy is necessary to decide, which type of control makes sense for the plant. There are commercial and non-commercial computer-based programs, which can calculate the pay-back-time and so help to choose the control type.

The components of a life cycle cost analysis typically include initial costs, installation and commissioning costs, energy costs, operation costs, maintenance and repair costs, down time costs, environmental costs and decommissioning and disposal costs. All the costs mentioned above have to be considered to decide, which kind of control type is the most economic for the specific case. It is therefore not possible to give general advice for one of the control types.

4 Properties and problems of the control modes

As already mentioned, tests have been made to find out if there are critical aspects for one of the control types. The first aspect to be discussed is the control itself. Are there any limitations for either of the control types? There are some limits for each of the control types. They will be discussed on the basis of the critical components of the pump or the plant.

The most critical component, causing approximately 60% of all pump failure in the chemical industry, is the rotating mechanical seal of the pump. Regarding the mechanical seal, three problems have to be mentioned: the temperature and the pressure around the seal, and the transport of gas or solids within the fluid.
The temperature in the seal is rising while the pump is running in partial load as long as the speed of the pump is not considerably reduced. This may be caused by throttle control or at speed control if the static head dominates the plant curve. The efficiency of the pump then decreases. At zero flow rate the fluid can not be actuated at all, so that all energy delivered from the pump must be converted into losses, resulting in heat. The temperature within the pump and around the sealing rises. At the test rig, after 10 minutes of running the pump against closed valves at nominal speed, the temperature was already at 48 °C and still rising. The pump did not have an insulating casing. The rise of the temperature is shown in figure 7. The solution to this problem is known and a standard in the chemical industry: It is the minimum flow through the bypass. With the bypass opened at approximately 2 to 5% of the nominal flow the seal was not heating up at all. If zero flow rate is adjusted, the valve has to be closed in case of throttle control and speed control. So a back-flow through the piping system is not possible and the pump can be stopped. The same procedure can be used with speed control, as there has to be a leak-proof valve in the piping system anyway to prevent a back-flow when mounting or exchanging the pump.

![Temperature within the seal](image)

Figure 7: Temperature within the seal

With gas in the fluid a ring of gas is separated in the impeller side gap in front of the seal. This ring prevents fluid from getting into the seal. Damage will be the result. With solid particles in the fluid the particles can get into the seal or prevent fluid from getting into the seal. The friction is increasing as well as the abrasion.

In figure 8 one result of the tests is shown. The adjusted flow rate is shown in pink, the flow rate with speed control in blue and the flow rate with throttle control in red. The flow rate was changed from 16m³/h to 4m³/h with both control types. At first sight, with speed control the selected flow rate seems to be reached quicker, but the point of stable control is the same with speed and throttle control, at approximately 40 seconds.
The measurements itself on the test rig showed no principle limits to either of the control types. Even the rapidity of the control types was nearly the same, depending on the selected parameters of the controllers.

5 Summary and Conclusion

While energy is getting more expensive, the economic pressure on the chemical industry is rising. The use of speed control can save energy. The amount is largely depending on the kind of plant. In plants with low static parts of the head, where the dynamic losses are dominating the curve, speed control is very reasonable, while in plants with high static parts of the head mostly throttle control is, for economic reasons, the better device. From the control-orientated point of view there is no difference between both kinds of control. With both types, there are some things to take heed of. While a bypass is necessary for throttle control in general, it is normally only necessary for speed control at plants with small dynamic losses. The advantages of the throttle control are: The system is less complex; investment costs are smaller. The disadvantages are: At partial load and with high dynamic part of the head of the plant, high losses occur while throttling, and maybe a bypass is necessary; no compensation of “wrong” pump curves. The advantages of speed control are: Compensation of “wrong” pump curve by varying the speed of the pump; at plants with high dynamic parts of the head of the plant, energy saving is possible; the engine is a soft-starter because of the frequency converter; no additional valve in the piping system. The disadvantages are: Zero flow rate may be problematic; a leak-proof shut-off valve is necessary; higher investment costs; parasitic frequency may occur in control signal or power supply system. A combination of speed and throttle control may be the best solution, depending on the used pump.

Normally only the investment costs will be considered, but a calculation of the life cycle costs is essential to find out the best solution.
6 References


A Tool to Identify Energy Saving Potentials of Motor Driven Pump Systems

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Abstract
It has been common knowledge for quite some years now that sound investment decisions should essentially be founded on the total life cycle costs - and yet, this is not always observed in the practice. For obvious reasons: There are some major hurdles when translating this knowledge into practice, such as the verification of relevant LCC data, the lack of compatibility with the planned budget, and the cost problematic of plant engineering. In the end, it is often the concluding quantitative assessment of the increase in productivity which is lacking. It is exactly this final assessment, however, which is required to use life cycle costs calculations efficiently.

It is relatively easy to obtain data for the energy costs; in the case of operation, maintenance, repair and downtime costs, however, it is much harder to gain relevant, statistically verified data, especially in relation to the life cycle costs over a certain period of time. Even when looking at the energy costs it must be taken into account that the load profile of the pump system has a significant impact on the total life cycle costs.

We have developed a software program which enables the user to compare the life cycle costs of different technical solutions. This tool is especially suited to determine the cost benefits of speed controlled drives and diagnostic systems, as well as of new technical solutions. Its calculations can further include the "added value" of conventional variants of a higher quality, e.g. regarding material, seal elements or energy-efficient drives.

An example from the practice illustrates the features and key elements of this tool. The computed results are displayed in a clear and structured manner, enabling operators and consultants to make efficient and sound investment decisions based on clearly defined assumptions. This presentation features a software program which has been developed to support technical argumentation and to translate technical discussions into the language of applied economics.

1 Introduction
As electric motor applications account for a large share of electricity use, they are more than likely to offer great potential for saving energy. Against this background, organizations like EUROPUMP and the US Hydraulic Institute (HI) have published a guide [1] which is intended to help pumping system owners and operators identify opportunities for cutting energy expenses and other costs. The LCC guide gives technically and economically relevant information, offers guidance on performing the analysis and includes sample calculations. A reference LCC analysis, which is also available as an Excel spreadsheet, is provided to make things as easy as possible for users.

A major challenge in putting life cycle costing into practice has been and still is the quantitative assessment of productivity improvements. Any evaluation of the economic benefits of a particular technical solution compared with alternative systems requires reliable data on the individual cost elements. As far as energy costs are concerned, these might be relatively easy to obtain. The cost of operation, maintenance, repair and
downtimes, as well as the intervals at which these will be incurred (MTBF, MTBR, etc.) are far more difficult to assess. But even energy costs may require an analysis in greater detail, in particular when it comes to the pumping system's actual load profile. The approach taken to overcome the obstacles described above is to use relevant LCC data to generate quantitative information as a basis for systematic and fast decision-making. A dedicated software has been developed which helps users compare the life cycle costs of alternative technical solutions. One of the findings that emerged from a close dialogue with plant owners and operators is that a direct comparison of different solutions, based on identical conditions, is deemed to be an important step towards cost transparency, since otherwise it is close to impossible to produce a correct forecast of the total cost involved. Problems may arise, for example, because there is insufficient information on the mode of operation available at the planning stage, or because the operating conditions change or because there are other unplanned influences. The software described below is intended as a tool to support the technical reasoning base and discussions on technical aspects while translating the (cost) benefits into business language.

Decisions on investments are typically made with a strong focus on profitability. Projects and measures must amortise over a given period of time. This means that achievable savings should be made transparent at an early stage. An overall LCC analysis of pump operation within a system will help identify and quantify potential cost reductions, both in terms of energy saved and other benefits, which can be realised by selecting suitable products, for example, improved system availability and productivity increases, reduced maintenance and lower repair costs, improved capacity utilisation, lower decommissioning and disposal costs.

2 General approach

As already mentioned, the calculation methodology is mainly founded on the EURO-PUMP / HI guidelines. However, the tool also incorporates extensive, empirically established data (incl. statistical analysis of customer information) and statistical information on equipment failure frequency in correlation with redundancy and monitoring. Default values based on the available empirical data are suggested for all cost elements. These may be overwritten by values furnished on the basis of the plant operator's own experience.

The underlying principle is that each analysis provides a comparison between alternative technical solutions, for example a comparison between fixed speed and variable speed pump operation. This means that only one parameter or a limited, "manageable" number of parameters is varied. In this way, the cost sensitivity of the individual parameter(s) can be examined. A typical set of parameters is shown in the screen print of Fig.1. The insight gained through a constant dialogue with pump users, both on general topics and in project meetings, underlines that this approach, i.e. a fast comparison of potential costs by varying particular cost elements, can speed up decision-making.
processes. It is precisely the variability of the assumptions that "generalises" the calculation and thus automatically highlights the cost elements which are of particular significance for the plant operator. There is no risk of "miscalculation" – if you do not have exact data for any of the cost elements, you just experiment with the options in order to assess their relevance for costs over the entire period under review. The additional payback information provided supports decision-making.

Comparative calculations can also be used to sketch out innovative solutions with all their benefits for the pump user. In the final analysis – even if this is not always considered right from the start – these are cost benefits.

2.1 Example: cost benefits through variable speed pumping systems

As it is well known, variable speed pumping systems run at or close to their best efficiency point (BEP). The resulting benefits are:
- Energy savings
- Longer maintenance intervals thanks to reduced loads on the pump
- Fewer repairs and lower risk of failure
- Reduction in downtime costs

Depending on the plant's overall configuration, speed control may also help reduce the number of different pump sizes required. One pump size might, for example, be used for different requirements or planned plant extensions. Integration of the control system in the pump/motor set may greatly simplify installation and operation. There are, of course, physical limits to the cost benefits to be achieved by variable speed operation, for example in systems with low piping losses or high static components. In addition, the volume flow rates at which the pumps actually run need to be considered, and it must be examined whether the designer possibly oversized the system by including safety allowances, etc. A series of comparative analyses must be performed for the system under review in order to assess the numerous parameters that influence the overall cost of the pumping system over its life span and to compute the payback periods. After first sensitivity checks of the parameters involved the analysis will quickly yield the answer to the one question of paramount importance: will speed control pay off or not? If the answer is negative, other alternatives may have to be explored (for example changing the impeller diameter to match the operating conditions of an installed system, etc.). But in any case a general direction of approach will be quickly recognised.

The following illustrations and diagrams provide information on a pumping system designed for a volume flow rate of 280 m³/h and a discharge head of 45 m. The best case scenario is that the pump is always running at full load, i.e. at optimum efficiency. Pump characteristic and system curve intersect at the pump's best efficiency point. It is evident that variable speed operation would not offer an advantage; the additional in-

Figure 2: Case study: total costs over 10 years for operation at design point and oversized pump due to safety allowance acc. to system curves
investment would simply not pay off. The overall picture is completely different for a pump that has been oversized to include safety allowances. The diagram shows the conditions for a situation where the influence of the installed valves (flow resistance with the valve fully open and, additionally, throttling to produce the rated volume flow), at constant volume flow rate, results in constant energy conversion. The analysis looks quite different now, see Fig. 2.

Figure 3: Case studies: total costs over 10 years for operation at certain load profile (distribution: 5% operation time at 25% of Qn; 30% operation time at 55%, 80% and 100% of Qn; 5% at 110% of Qn). top: plant w/o safety allowance, bottom: oversized pump.

In most applications, however, the pump is not always run at BEP, but also under off-design conditions (low flow / overload). Some branches of industry, such as for example water utilities, have quite reliable load profile data, i.e. information on the flow rate pattern over time, which can be taken into account in the analysis. Industrial companies usually do not have detailed data of this kind. In this case, an estimated load profile may be used for the profitability analysis. Since the same load profile is assumed for both technical alternatives, i.e. for variable speed and fixed speed operation, comparability of the results is ensured for all scenarios. You could also, for example if the calculated payback period borders on a given limit, repeat the analysis with stricter assumptions and more constraints on parameters. The results will always speak for them-
selves (Fig. 3). In-house experience with maintenance and repair schedules for electrical equipment may also be considered and evaluated.

In some instances, a pumping system is initially run under part-load conditions for some time because it has been designed for a rated volume flow rate that will only be achieved once the overall system it is installed in has been completed. This case was simulated as well (Fig. 4), and the results reveal that even for a relatively short period of part-load operation a control system or speed adjustment (in this case constant) would improve profitability. Another option would, of course, be operation of two 50% pumps.

![Figure 4: Case study: total costs over 4 years for constant operation at 50% part load and for oversized pump due to safety allowance.](image)

All the examples described consider pumping systems with dynamic losses only, i.e. without static head component. If we want to take this important parameter into account, we need to use a different system curve for the hydraulic analysis. In this case, the static head is taken to be $H = 35$ m, see Fig. 5. With increasing static head, the profitability rating of a pump control system will, as you know, change for all assumed load profiles and other system conditions (safety allowance included or not, etc.). Although this is not exactly a new finding, the examples given underline that the absolute value is of major importance for the subsequent decision-making process. There must be a shift in focus at the earliest possible stage of this process. The qualitative technical assessment “is better / worse” needs be rephrased to reflect relevant business information: "What are the savings over which period of time?". And, despite all the facts, assumptions and imponderables to be contemplated in practice, it must be possible to give a fast and reliable answer to this question.
2.2 Example: cost benefits through condition monitoring and diagnosis

Additional functions like pump monitoring and diagnosis generally improve system availability. They facilitate low-cost, predictive maintenance and thus reduce operating costs. Obviously, evaluation of the signals and data obtained directly from the pump is not intended to compensate for shortcomings in pump design, but needs to be seen in the wider context of comprehensive system monitoring. Correlating actual data with the supplier’s know-how regarding the typical response of pumps and systems to off-design conditions provides valuable information, which can be applied to reduce the above-mentioned cost elements. In state-of-the-art systems, pumps can, for example, serve as "system monitor". Energy expenses and longer maintenance or repair intervals frequently offer the greatest scope for minimising LCC. But where critical or sensitive systems are concerned, the need to keep production processes going may have
top priority because the cost of lost production would be unacceptably high. In these cases, additional investments in monitoring equipment may amortise very quickly.

The diagrams in Fig. 7 and 8 highlight the impact on costs of diagnostic equipment for various cases in order to demonstrate the general effects. It is assumed that the pump user has sufficient experience to judge whether, and if so, to what extent, a system must be regarded as critical or not. Usually statistical data are available on how often pumps are likely to fail in a given period of time (MTBF) and what the mean time to repair (MDT) these pumps is. The values are used to calculate the availability of the individual pumps (statistical mean) and assess the effects on overall system availability. If redundancy is "built into" the system, it is not very likely that two pumps fail at the same time. This is accounted for by applying probability laws and calculations. It is clear to see that the use of diagnostic equipment has a positive effect on costs where critical systems are concerned, i.e. when there are short intervals between outages, when there is no redundancy and if different assumptions are made regarding downtime costs or loss of production. Again, qualitative technical advantages need to be translated into understandable and reproducible business statements. Reproducibility is ensured by the variability of the assumptions that can be made for the individual cost elements.
3 Summary

In the present paper a comparative LCC evaluation approach and a respective software tool is described, which allows a quick estimation and an easy-to-use calculation of LCC cost benefits under various assumptions and conditions. Applying this tool, several case studies and different industrial applications are demonstrated. The cases shown highlight the cost benefits offered by control systems, diagnostic systems and new technological developments. Absolute values of the calculation results in term of Euros are output and enable users to make fast decisions on investments.

Reference

ProMot Pump Module: Helping to Find the Most Efficient Saving Actions for Pumping Systems

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Abstract

This paper presents the ProMot Pump Module, a simple and easy-to-use software tool that helps users to find the most cost and energy efficient solution for purchase and replace decisions of pumping systems. The ProMot pump module incorporates the Europump guidance procedure for selecting single stage centrifugal pumps as well as a VSD module that supports the evaluation of energy savings using variable speed operation. On the basis of a load profile energy and cost savings as well as payback times can thus be calculated for different scenarios: using an EFF1 motor, using an optimized pump and operating with variable speed. The module is part of the freely available ProMot decision support tool.

1 Introduction

An optimal configured pumping system offers many advantages such as improved quality and production rates, reduced noise and vibrations and last but not least reduced energy consumption and operating costs.

Figure 1: Head and efficiency of a centrifugal pump at constant speed
In many cases pumping systems are operating very inefficiently and thus are offering an important source of saving opportunities. However most end users, as well as distributors and consultants often lack the time to find the most efficient solution. This is mainly due to fact that the efficiency of pumps varies significantly with head and flow. Simply comparing the nominal efficiency of pumps is therefore not feasible. The characteristics of centrifugal pumps expressed as head and efficiency against flow can generally be approximated by parabolic curves such as shown in figure 1. For a single pump running at constant speed, the usual way to reduce the rate of flow is to increase the system head by means of throttle control using valves or vanes. This method simply increases the friction losses and leads to reduced efficiency and service life of the system. Varying the rotational speed has a much better effect: the pump head can be reduced while keeping the efficiency nearly constant. The variation of head and flow related to speed is described by the so called laws of affinity. The resulting curves for head and efficiency at different speeds are shown in figure 2.

2 Efficiency Analysis

The procedure to compare cost and energy efficiency of pumping systems are well documented (see References for further information). Some simple and in many cases feasible actions that should be investigated are:
1. Replacing the motor by an EFF1 High efficiency motor,
2. Replacing the pump by a pump with optimized efficiency,
3. Using a variable speed drive instead of constant speed,
and any combination of these. To support this procedure SEMAFOR has developed the pump and VSD module that is now included in the ProMot decision support tool. The current version 1.4 covers centrifugal pumps for clean water applications.

Figure 3: Main Dialog

Figure 3 shows the main dialog that appears after starting up the module. The dialog includes three top-level sheets:

1. **Pump**: the description of the pump component, its nameplate values and optionally its type and efficiency area.
2. **Load Profile**: the description of the operating characteristics.
3. **Energy, Cost and Savings**: the description of the relevant economic data and the calculated results: energy consumption, total cost and expected savings for different saving actions.

3. **The EU Efficiency Classification**

After entering the nameplate values of the pump, the efficiency area according to the EU pump guide procedure can be determined provided that the pump type is given. Based on published efficiency data from many manufactures the procedure defines three efficiency areas: low efficiency, efficient and optimum efficiency selections. These areas are separated by two lines: the lower and the upper level line.

![Efficiency Area Plot](image)

**Figure 4**: Resulting efficiency area plot with nominal operation point

The results of this calculation are shown in the field “Efficiency Area” with a background color that is related to the resulting value: red for low, yellow for efficient and green for
optimized. A more detailed view can be seen on the sheet “Efficiency Areas” which is shown in figure 4.

4 Load Profile

Figure 5: Load Profile Dialog

The operation characteristic is described by the load profile. It can be given either as estimated or as measured flow rates depending on the state of the check box "Estimated Flow". If this check box is selected, the values can be entered as percentage values of the nominal flow rate otherwise as real values in m³/h. The same applies to the static head value, which specifies the level difference between the pipe and discharge height and the fluid surface height in the suction tank. The fraction values specify the operating time as a fraction of the total operating time per year at each of the listed flow rate. The sum of the fraction values must be less or equal to 1.
5 Energy, Costs and Savings

Figure 6: Calculation Results

This sheet shows the calculated results of energy consumption, cost, savings and pay-back for the following variants:

1. This pump with an EFF3 Standard efficiency motor at constant speed,
2. This pump with an EFF1 High efficiency motor at constant speed,
3. An optimized pump and an EFF1 High efficiency motor at constant speed,
4. An optimized pump and an EFF1 High efficiency motor with variable speed operation

based on the energy price, the demand charge, the operating hours, the installation and purchase prices and the given load profile.
6 Catalogue Database

With an integrated component database including pumps from various manufacturers the implemented selection and decision support procedure could be further improved and simplified. However, without a broadly accepted standard the collection and import of pump data from different sources would be a tedious and time-consuming process. Such a standard, the "VDMA Einheitsblatt 24278", has been created by the German industrial associations VDMA (engineering industries) and VCI (chemical industry). It contains the specification of data exchange between pump manufacturers and users. Based on this standard SEMAFOR has already implemented a catalogue database with an interface to easily import pump data. It was included in the pre-release version of the ProMot pump module. Discussions with Europump representatives have now lead to the decision to remove this feature from the final version. For a future release the following options should be evaluated:

1. Providing a catalogue database with the pump data of interested manufacturers
2. Implementing a general import function that allows each user to include pump data individually.

7 References


Predictive Maintenance of Centrifugal Pumps

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Abstract

This work has been initiated to fulfil the industrial demand of the pumps manufacturers. This paper deals with diagnosis solutions that enable to detect in real time early mechanical, hydraulic or processing failures on centrifugal pumps.

A test bench with a centrifugal pump and a closed loop circuit has been installed. A set of non intrusive sensors have been mounted on the pump body.

Time and spectral analysis on acquired signals enabled to identify faults linked with the mechanical and hydraulic behaviour. To generalise the results of the study, tests have been carried out with another centrifugal pump and a software interface has been developed with Labview®.

In order to provide an industrial solution and facing the necessity to treat very different cases of pumping plants, an approach using neural networks and neurofuzzy technique has been developed. A prototype of a diagnosis system has been implemented with success on the test pump installation allowing to process data in real time with an easy interfacing procedure.

1 Introduction

The maintenance costs in the pumping installations reach a high level compared to the exploitation budget. In this context, the French manufacturers association (AFPR) and the CETIM initiate a study concerning the early detection of recurrent defects in the centrifugal pumps, the final objective of this study, being the development of an on-line and real-time diagnosis system. Such diagnosis system would be really useful because a lot of the pumping installations are isolated, without anyone working on-site. The following approach has been used in the study:

• Development of the diagnosis methodology,

The study started with the identification of the pertinent defaults to be monitored, in collaboration with industrial partners. Then a pumping test-rig was designed to simulate this defaults and characterise their signature based on a set of sensors. Forms summarising the signature of each defect have been edited.

• Generalisation of the method: industrial application,

To validate and generalise the first results, a second test-rig has been designed, with a different pump in an environment closer to an industrial one. The most pertinent sensor was chosen, and the whole diagnosis method was developed based on this single measurement. A prototype of the diagnosis system has been implemented, based on the forms previously established.
Neural networks based approach,

The implementation of a diagnosis system has to take into account industrial conditions, and especially that the behaviour of pumping installation are different from one site to another. Each time it is necessary to adjust the threshold levels of the monitoring parameters. This operation is quite long and sensitive. To solve this problem, a monitoring system has been developed, based on neural networks and neurofuzzy techniques.

2 Development of the Diagnosis Methodology

2.1 Selection of the type of failure to study

The first step of the study was to work in collaboration with the pump manufacturers to choose the defects to monitor. Among the fifteen defects first listed, seven have been selected for this study. They include mechanical defects, hydraulic ones and process operating conditions and are presented below:

Mechanical faults
- loosening of front/rear pump fastenings, - misalignment,
- rotor-stator contact.

Hydraulics faults
- air injection at the inlet,
- partial flow blocking (obstruction between two blades).

Process operating conditions
- cavitation,
- partial flow rates.

2.2 Test rig installation and programme of the tests

A test-rig was then developed at the CETIM facility. The tested pump (Figure 1) has been installed in a closed loop circuit enabling to simulate the faults.

In the context of this study, that takes into account the industrial applicability to a pumping plant process monitoring, the non intrusive sensors have been promoted. Therefore, the pump has been equipped with accelerometers, acoustic emission sensors and current measurement sensors (figures 2 and 3). Nevertheless, in order to validate the fault to signal correlation, intrusive sensors (pressure and displacement) have been added. A number of 17 sensors has been used (table 1).
Figure 1: Closed loop test-rig installation

Table 1: Sensors identification

<table>
<thead>
<tr>
<th>γ (1 to 8)</th>
<th>Accelerometers</th>
</tr>
</thead>
<tbody>
<tr>
<td>D (1 and 2)</td>
<td>Displacement sensors</td>
</tr>
<tr>
<td>EA (1 and 3)</td>
<td>Acoustic emission sensors</td>
</tr>
<tr>
<td>MS (1 and 2)</td>
<td>Mecason® sensors</td>
</tr>
<tr>
<td>P (1 and 2)</td>
<td>Pressure sensors</td>
</tr>
</tbody>
</table>

Figure 2: Sensors location

Figure 3: Instrumented pump
In this paper flowing, only the results based on the acceleration measurements will be detailed.

Each default has been successively simulated and the signals of all the sensors have been acquired in a large band of frequency (0-12800 Hz). The signals were processed, mainly based on narrow band spectral analysis.

From these analysis, overall vibration levels calculations, in specific bands of frequency have been chosen. In particular, in view of the first results, two bands of frequency have been selected:

- the first one, a low frequency band [0 - 1600] Hz, sensitive to all the cinematic phenomena,
- the second one, a larger frequency band [0 - 12800] Hz, includes the first one but is also sensitive to the vibrations created by hydraulic phenomena.

In order to characterise in a more precise way the modifications induced by some defaults, the amplitude of the peaks corresponding to cinematic frequencies, have been used as monitoring parameters:

- the rotation frequency peak and its harmonics: \( H_1, H_2, H_3, H_4 \) and \( H_5 \),
- the peaks related with notch passing frequency of the motor rotor and stator: \( H_{40} \) and \( H_{44} \).

To process the current signals, spectral zooms have been used in order to identify, in a precise manner, frequency modulations. In the same manner, the use of zooms was necessary to identify precisely the rotation speed based on a high harmonic (\( H_{100} \)) of the tacho signal.

2.3 Results

This first phase of the study enabled to establish the relationship between the measured signals and each default depending on:

- the sensor type (accelerometer, acoustics emission, current.... ),
- the positioning on the pump body,
- the monitored parameter (type of processing).

The analysis of these results also enabled to select the non intrusive instrumentation depending on the monitoring criteria. For example, we show (table 2) a synthesis form concerning the cavitation.
Table 2: Synthesis on cavitation detection

<table>
<thead>
<tr>
<th>Available tools</th>
</tr>
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<tbody>
<tr>
<td>Measurement using vibration sensor</td>
</tr>
<tr>
<td>Sensor: 1 accelerometer axially positioned on the casing</td>
</tr>
<tr>
<td>Parameter used: overall level in the band of frequency (0 -12800Hz)</td>
</tr>
<tr>
<td>Measurement by Mecason sensor®</td>
</tr>
<tr>
<td>Sensor: 1 sensor positioned vertically on the packing ring</td>
</tr>
<tr>
<td>Parameter used: overall level in the band</td>
</tr>
<tr>
<td>(100 -12800Hz)</td>
</tr>
<tr>
<td>Measurement by acoustics emission</td>
</tr>
<tr>
<td>Sensor: 1 sensor broad band positioned on the body</td>
</tr>
<tr>
<td>Parameter used: counting rate</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Criteria of choice</th>
<th>Vibration</th>
<th>Mécason ®</th>
<th>AE</th>
</tr>
</thead>
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<tr>
<td>Sensitivity / environment</td>
<td>+</td>
<td>+</td>
<td>o</td>
</tr>
<tr>
<td>Easiness of installation</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Shift in of the sensors</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Sensitivity / defect</td>
<td>+</td>
<td>+</td>
<td>++</td>
</tr>
<tr>
<td>Easiness of use</td>
<td>+</td>
<td>+</td>
<td>o</td>
</tr>
<tr>
<td>Cost</td>
<td>+</td>
<td>+</td>
<td>o</td>
</tr>
</tbody>
</table>

Legend: --: Very bad ; -: bad ; o: average ; +: good ; ++: very good

3 Generalization of the Method

In order to generalize the results of the study, tests have been carried out with another centrifugal pump whose rotating speed is higher (see figure 4). The mechanical and hydraulic characteristics of this pump are the following:

The pump has been installed in an opened loop circuit and equipped with only one sensor, an accelerometer located on the bearing of the pump.

On this pump, the same defaults have been simulated and for each configuration the vibration signal has been measured in a high frequency band.

The diagnosis rules previously established (see the forms), have been used to develop a prototype of a monitoring system.

To acquire and to analyse the signals of the sensor, a software interface has been developed with commercial Labview® software using an acquisition card (NI 4552 (National Instrument)).[3]
The man-machine interface of the monitoring system includes two windows:

- a window (figure 5) dedicated to acquisition and signal processing parameters,
- another window with a set of view meters and indicators of status (figure 6) showing the information on the status of the pump and therefore on the simulated default.

The initialization of the diagnosis system requires the following steps:

- Operating of the pump without any fault to initialize the monitoring parameters,
- Setting of the detection thresholds for each default independently,

The results reached with this prototype are quite satisfying and it is able to detect on-line the different defaults.

Even so, this prototype is very interesting from a tutorial point of view (this test-rig has been used to demonstrate the pump monitoring for pumps manufacturers), it seems sometimes difficult to tune the thresholds. The monitoring parameters chosen for each fault are not completely independent and the simulation of one fault sometimes creates some changes in the monitoring parameters of the other faults. This might lead to some difficulties to identify separately each fault.

To solve these difficulties and to face the necessity to integrate very different cases of pumping plants, another approach using neural networks, as a diagnosis tool, has been developed.
Figure 5: Man-machine interface of the monitoring system – Acquisition parameters

Figure 6: Man-machine interface of the monitoring system – View meters of the status of the pump
4 Neural Networks Based Approach

4.1 Principle

Neural networks allow to automatically diagnosis a default from a multi criteria analysis and then to be able to separate the signature of each default. Their implementation is based on two steps [4]:

- a learning phase, where it is necessary to provide the neural networks with observations (signals) of each default and of a non-faulty state, so the networks learn to classify them,

- a diagnosis phase, where the neural networks are able to identify on-line the status of the pump.

In this part of the study, the same instrumentation as previously, which is a single acceleration sensor, has been used. From this signal, 13 parameters have been extracted and are the input data for the neural networks.[1],[5]

Two architectures have been tested for the neural networks. The first one, where a single neural network was used, to classify all the defects. And a second one, where a neural network per defect was used (each network learning to identify one class). The second architecture gave the best results and is the one implemented in the diagnosis system. In addition, this kind of architecture, based on neural networks, enables to reject any observation, that would not correspond to a known class (known defect).

Among the faults taken into account, two have been simulated with gradual level (for example the flow rate varies in our tests from 0 % to 128 % Qn and the cavitation varies from NPSH-1 % to -6% ). To improve the classification results on these two faults, neuro-fuzzy techniques have been included. [2]

Neuro-fuzzy systems are defined as a combination of neural network with Fuzzy Inference System (FIS) and are based on three steps:

- fuzzification: each input is assigned to each state with a membership degree,

- inference: “If-then” rules are applied to input variable to obtain output membership degrees.

- defuzzification: a decision is taken based on the output membership degree.

Considering the complexity of the neuro-fuzzy learning algorithm, the number of inputs had to be reduced from 13 to 2 or 3, using a discriminant analysis based on Fisher criterion.

4.2 Results

The results obtained are rather satisfactory for the defaults as shown in the following table.
Table 3: Classification rates

<table>
<thead>
<tr>
<th>Type of defect</th>
<th>Classification rate (%)</th>
</tr>
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<tr>
<td>Flow rate ($\gamma$, $Q_n$)</td>
<td>100</td>
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<tr>
<td>20 %</td>
<td>100</td>
</tr>
<tr>
<td>40 %</td>
<td>100.</td>
</tr>
<tr>
<td>60 %</td>
<td>100</td>
</tr>
<tr>
<td>80 %</td>
<td>99.93</td>
</tr>
<tr>
<td>112 %</td>
<td>99.7</td>
</tr>
<tr>
<td>128 %</td>
<td>100</td>
</tr>
<tr>
<td>Misalignment</td>
<td>99.7</td>
</tr>
<tr>
<td>Rear attachment loosening</td>
<td>100</td>
</tr>
<tr>
<td>Front attachment loosening</td>
<td>100</td>
</tr>
<tr>
<td>Cavitation 1 %</td>
<td>99.75</td>
</tr>
<tr>
<td>3 %</td>
<td>99.75</td>
</tr>
<tr>
<td>6 %</td>
<td>99.75</td>
</tr>
<tr>
<td>Air injection 9 l/mn</td>
<td>98.8</td>
</tr>
<tr>
<td>15 l/mn</td>
<td>99.95</td>
</tr>
<tr>
<td>Without default</td>
<td>99</td>
</tr>
</tbody>
</table>

4.3 The Diagnosis System

As previously, LabView® was used to develop a software interface for the monitoring system, whose principle has just been described.

The software interface includes:

- the acquisition of the signals,
- the processing of the signals to extract the monitoring parameters,
- the learning phase of the neural networks,
- the classification phase as an on-line monitoring system.

Four windows (figures 7 to 10) illustrate each stage from the signal acquisition to the diagnosis:

- the first window controls the acquisition allowing different adjustments like the sampling frequency, the resolution, the number of acquisition,
- the second window controls the learning phase of the neural networks,
- the third window is the interface for on-line monitoring, showing a red light to indicate the fault identified or a green light if there is no fault on the pump,
- the fourth one and last one shows a representation of the level of each parameter using view meters.
5 Energy Efficiency Consideration

The objective of using a predictive maintenance programme is mainly to prevent a disastrous equipment failure and to minimize the maintenance cost.

However, if we considered that a pump is adjusted to work at its best efficiency point on a circuit, a flow rate variation or a cavitation phenomena could occur and affect this efficiency. In such a case, our diagnosis system could detect the failure and can avoid the loss of 2 or 3 points of efficiency.

6 Conclusion and Perspectives

This study realized on centrifugal pumps monitoring, enabled to improve the knowledge on the signature of critical defects using non intrusive sensors. Taking into account, the industrial objectives (cost, reliability,...), it was possible to minimise the number of sensors, and in this application, only one accelerometer is needed.
Experiments have been carried out on two different pumping test-rigs, with coherent results. Two prototypes of monitoring systems have been developed, providing a user friendly interface. The classification results are good (from 98.8 to 100 % depending on the defect).

The robustness of the diagnosis system to the variability of the monitoring parameters in function of the installation (hydraulic and mechanic characteristics) and also in function of the process conditions, needs to be further studied. So the next step will concentrate in testing the system in different industrial environments.

7 Acknowledgements

We would like to thank the AFPR working group representing French pump industry under which these studies have been sponsored.

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Following the success of the first three meetings in Lisbon (1996), London (1999), and Treviso (2002), the European Commission and the Fraunhofer Institute for Systems and Innovation Research are organising the 4th International Conference on Energy Efficiency in Motor Driven Systems to be held in Heidelberg, Germany September 5th to 8th, 2005.

The previous EEMODS events have been very successful in attracting an international and distinguished audience, representing a wide variety of stakeholders in the development, manufacturing and promotion of energy-efficient motor systems.

EEMODS '05 will provide a forum to discuss and debate the latest developments in the impacts of electrical motor systems on energy and the environment, the policies and programmes adopted and planned, and the technical and commercial advances made in the dissemination and penetration of energy-efficient motor systems.

The conference’s technical focus is on industrial motors and motor systems, where the replication and savings potentials are the greatest.
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MCP Experience
The European Motor Challenge Implementation at Centocor Leiden

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Abstract

The "European Motor Challenge Program" Partner Guidelines are effective Engineering Design tools to achieve energy efficiency of motor driven systems and Operational Excellence whilst reducing the emission of Greenhouse gases.

Utilization of high efficiency Low Voltage Electric Motors, with the possible combination of Variable Speed Drives, can lead to higher system efficiency, longer equipment availability time, and reduction in maintenance and operation costs whilst reducing the emission of Greenhouse gases.

The extra capital investment costs for newly built motor systems are negligible in comparison with the emission reductions and savings gained during the life cycle of the technical system.

However for the smaller existing motor driven systems it is difficult to achieve financial justifications for modifying these that give a reasonable pay back time.

The Motor Challenge Guidelines for new motor driven systems are the perfect tools to use for Engineering Standards, resulting in better system performance and life cycle improvement.

Compliance with the Motor Challenge Program leads to emission reduction but will also always be an inseparable part of the total motor system performance process.

High efficiency motor driven systems that are not properly maintained and monitored do not lead to any added value.

Regular energy audits must be included in the life cycle process.

Pharmaceutical companies are part of a very precisely operating industry as regards process changes because of the stringent documentation requirements required for these changes.

Implementation of the Motor Challenge Program is a process that requires patience and careful preparation to achieve the best final results.

This article gives an overview of the steps followed, the advantages and disadvantages as well as the expected benefits in the future.

History

As a result of a merge with the Johnson & Johnson Company in November 1999, Energy Management became an inseparable part of our sound Technical Operations.

The respect for our environment is embedded in the Johnson & Johnson Credo in the following sentence,

"We must maintain in good order the property we are privileged to use, protecting the environment and natural resources”.

Besides the environmental responsibility there is an economical responsibility embedded in the following sentence.

"We must constantly strive to reduce our costs in order to maintain our prices”.

The EU Motor Challenge Program (1) is besides many other Energy Management Programs an excellent tool to assist companies in fulfilling their commitments to the society when trying to reduce their energy usage and Greenhouse Gas emissions.
Centocor B.V. as affiliate of the Johnson & Johnson Corporation decided as of the initiation of the EC Motor Challenge Program to apply for membership, which finally resulted in an early Partner registration to the Motor Challenge Program in 2003.

**The EU Motor Challenge Program at Centocor**

In accordance with the Motor Challenge Partner Guidelines a company action plan was initiated.

To create awareness, understanding and acceptance regarding the M.C.P. a Company Motor Challenge Team is appointed consisting of members of the Engineering as well as the Operations Departments.

The main objective of the team was defining the scope and ascertains the applicability of the criteria for motor drives and motor efficiency classes.

The team decided to create a new electro motor inventory list suitable for the Computerized Maintenance Management System and for the site inventory resulting in a survey of all electric motors with a capacity greater than 0.37 kW not being part of an integrated systems e.g. Chiller motors, see table 1.

**Table 1: SAP input file**

<table>
<thead>
<tr>
<th>Description</th>
<th>Units</th>
<th>Number of Barcodes</th>
<th>Type Format</th>
<th>Type of overreaching</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed</td>
<td>rpm</td>
<td>4</td>
<td>Number</td>
<td></td>
</tr>
<tr>
<td>Voltage</td>
<td>V</td>
<td>5</td>
<td>Number</td>
<td></td>
</tr>
<tr>
<td>Special features</td>
<td></td>
<td>4</td>
<td>Number</td>
<td></td>
</tr>
<tr>
<td>Load (average)</td>
<td>%</td>
<td>4</td>
<td>Number</td>
<td></td>
</tr>
<tr>
<td>Efficiency (average)</td>
<td>%</td>
<td>4</td>
<td>Number</td>
<td></td>
</tr>
<tr>
<td>Transmission type</td>
<td></td>
<td>4</td>
<td>Number</td>
<td></td>
</tr>
<tr>
<td>Control type</td>
<td></td>
<td>4</td>
<td>Number</td>
<td></td>
</tr>
</tbody>
</table>

![SAP input file screenshot]
More than 450 electric motors were identified in accordance with the Motor Challenge Guidelines.

During evaluation of the motor data a selection was made based on motor efficiency class, the applicability of motor drives and financial savings to be used for the first annual action plan.

The team also decided to adopt the Euro DEEM (2) as company motor efficiency standard resulting in an Engineering Guideline to ensure the commitments to the M.C.P., see figure 1.

![Guideline IEC drives](image)

Figure 1: Guideline IEC drives

In addition to the Motor Challenge inventory all older fan systems were evaluated on optimal transmission ratio, V belt speed, V belt span angle (angle of contact) and amount of bends per minute to evaluate the overall drive performance of a fan system. (figure 2)

Some older fan systems were subjected to capacity modifications during their life cycle. The simplest way to decrease the fan capacity is increasing the system resistance or reducing the diameter of motor pulleys. It is logical that a wrap angle of 180° will result in a maximal grip and the lowest slip. The greater the distance between the pulleys the less belt bends per time unit. The more bends per second the higher the heat generation in the V belt resulting in more slip.
All investigated drive systems had calculated slips within the acceptance criteria’s as advised by The University of Western Australia (3). (table 2).

However most of the investigated e motors of the fan systems appeared to be very oversized and will be modified with smaller motors and VCR’s.

The Air handling unit fan from table 2 for example has a calculated shaft power of 12.5 kW whilst the unit is equipped with a 28 kW electric motor.

Table 2: V-belt selection tool

<table>
<thead>
<tr>
<th>Belt type</th>
<th>Filler diameter [mm]</th>
<th>Belt speed [m/s]</th>
<th>Power transmission [kW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>15.1</td>
<td>5 m/s</td>
<td>1.2</td>
</tr>
<tr>
<td>B</td>
<td>16.8</td>
<td>10 m/s</td>
<td>2.5</td>
</tr>
<tr>
<td>C</td>
<td>20.3</td>
<td>15 m/s</td>
<td>4.0</td>
</tr>
<tr>
<td>D</td>
<td>25.4</td>
<td>20 m/s</td>
<td>5.5</td>
</tr>
<tr>
<td>E</td>
<td>31.5</td>
<td>25 m/s</td>
<td>6.0</td>
</tr>
</tbody>
</table>

Figure 2: Optimal wrap angle
As a result of the Motor Challenge program new design specifications were initiated for Chillers, Air Compressors, Pumping Systems and Fan systems focused on application of Euro DEEM and VCR’s.

Figure 3: Constant flow and e-motor reduction achieved with variable speed control
For 2005 improvements have been initiated for:

1. Creating a constant flow in existing HVAC units. In total 11 older Fan Systems will be modified with smaller motors and Frequency Controllers representing 16% of the total building load. Estimated savings are calculated at 86,800 kWh/year.

2. In total 6 older low C.O.P. operating Chillers with a thermal capacity of 3500 kW are to be replaced by one Centrifugal Chiller with Variable Speed Drive and combining 4 distribution systems into 1 distribution system. The energy saving as result of this replacement is 180,000 kWh/year.

3. An energy reduction of 56,900 kWh/year has been achieved by replacing 3 reciprocating Air Compressors of 28 kW each by two 37.5 kW Rotating Compressors with VSD including new Air dryers with VSD control.

4. Five Air Handling Units were downsized after evaluation and the electric motors were equipped with VSD drives resulting in an energy reduction of 166,200 kWh/year.

5. Six continuous parallel operating circulation pumps with in total 103 kW power installed are now equipped with Variable Speed Drives whilst only 3 pumps are in parallel operation which directly resulted in an improved system performance and a yearly energy saving of 154,400 kWh/year (See figure 5).

For those motor systems driven by motors with a range between 0.37 kW and 1 kW e.g. Central Heating circulating pumps a continuous replacement program for electronically controlled circulating pumps exists. See figure 4.

At present in total 20 conventional pumps with a capacity varying between 1 and 4 kW have been replaced for new generation pumps equipped with VSD resulting in a yearly saving of 52,000 kWh/year.

The total savings after participating the EU Motor Challenge Program is 644,000 kWh, as been reflected in table 3.
Table 3: Results MCP

<table>
<thead>
<tr>
<th>Project</th>
<th>Description</th>
<th>Savings [kWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Retrofit 11 recirculator Air Handling Units applied with frequency control and downgrading drive. By installing frequency control the efficiency of the ventilators of the Air Handling Units will increase with approximately 8%</td>
<td>68,800</td>
</tr>
<tr>
<td>2</td>
<td>Replacement 8 recoprocating chillers for one VSD controlled centrifugal chiller. COP recprococating chiller = 3; COP centrifugal chiller = 5</td>
<td>180,000</td>
</tr>
<tr>
<td>3</td>
<td>Replacement 3 recoprocating compressed air units for 2 VSD controlled screw compressed air units. Average overall efficiency recoprocating compressed air units = 60%; Average overall efficiency VSD controlled screw compressed air units = 80%</td>
<td>96,900</td>
</tr>
<tr>
<td>4</td>
<td>Replacement 5 ambient Air Handling Units for two VSD controlled Air Handling Units. Power consumption old Air Handling Units 100 kW =&gt; average efficiency 57%; Power consumption old Air Handling Units 85 kW =&gt; average efficiency 70%; Operation hours Air Handling Units = 8760</td>
<td>166,200</td>
</tr>
<tr>
<td>5</td>
<td>Retrofit 6 circulation/pumps applied with frequency control and IEC motor. Savings electricity consumption as result of applying IEC motors = 16.2% of total reduction; Savings electricity consumption as result of applying frequency control = 84.8% of total reduction; Applying frequency control will reduce approximately 20% of the total energy consumption</td>
<td>154,100</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>Total</strong></td>
<td><strong>644,000 kWh</strong></td>
</tr>
</tbody>
</table>

Obstacles during the first year

During the inventory and evaluation phase it became clear that many technical systems installed after 1990 were already in compliance with the efficiency classes as listed in the “Euro DEEM” database as Eff1 and Eff2.

To achieve the highest efficiency class for the existing systems most of the capital investments were too high to justify the additional costs, see for example table 4.

In a continuous 24/7 operating enterprise the availability of motor driven systems for modification purposes is another obstacle. Careful planning and communication is an absolute necessity to achieve success in your organization the lobby role of the Motor Challenge Team is very important in order to convince the different cultures within the various departments involved in life cycle management of the benefits and savings.

Regular communication and information as well as education are absolute requirements for success. Future support of Motor Challenge Endorsers to Partners might be a great help.

Expert Workshops with demonstrations concerning the Motor Driven Systems could be valuable.
Table 4: Investment versus savings

<table>
<thead>
<tr>
<th>Two-speed power rated in kW</th>
<th>11 kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Consumption old</td>
<td>kWh 72,270</td>
</tr>
<tr>
<td>Consumption new</td>
<td>kWh 69,668</td>
</tr>
<tr>
<td>Energy saving</td>
<td>kWh 2,602</td>
</tr>
<tr>
<td>Investment</td>
<td>€ 1,356,08</td>
</tr>
<tr>
<td>Recovering time</td>
<td>9.3 Year</td>
</tr>
</tbody>
</table>

Figure 5a: Initial situation with continuous velocity of 2.5 m/s

Figure 5b: Continuous pressure and variable velocity between 1.5 and 2.5 m/s

Figure 5: Improving hydraulics
Summary

The application of the EC Motor Challenge Guidelines as Engineering Standards does have many advantages. Especially older motor driven systems can lead to significant energy reductions when utilization high efficiency motors and motor drives in motor driven systems. For existing motor driven systems the financial justification is difficult to achieve. Intermediate system modifications should be used to achieve efficiency improvements.

Technical operation and monitoring must always be a part of the program, otherwise the capital investment is useless.

Future support of Motor Challenge Endorsers to Partners might be a great help.

Expertise from Motor Challenge Endorsers as promoters can help low staffed Technical Operation departments with the preparation of the yearly action plans.

References

1. http://energyefficiency.jrc.cec.eu.int/motorchallenge/

Figure 1. Centocor B.V.

Figure 2. University of Western Australia

Figure 3. Carrier Holland Heating the Netherlands

Picture 1. Grundfoss Nederland B.V.
Power Electronics and Drives
Energy Efficiency of Frequency-Controlled Electric Drive in Hoisting Gear Application

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Abstract

The paper deals with possibility of efficiency estimation of Frequency-controlled drive (FCD) in compare with traditional drives for two hoisting applications: gantry container crane and passenger elevator. For quantitative estimation of energy performances the simulation of different drive types for typical speed and load cycles was carried out. A developed program simulation block for energy consumption and losses calculation was used. The great advantages of FCD with respect to traditional drives are shown for different hoisting gear applications.

1 Introduction

The current level of power electronics and microprocessor tools for control and monitoring allows paying the attention to many areas of induction motor drives application from new point of view. The up-to-date durable and rather inexpensive semiconductor frequency converters (FC) in combination with automation tools make it possible to use these technical achievements extensively for energy saving purposes. Theoretical and experimental investigations allow determining the following main areas of their applications.

The first one is related with drive loss reduction during operation at reference load and speed cycles. These are the drives operating in start-stop mode (cranes, elevators, auxiliary servo-drives of rolling miles, etc) [1] or drives operating continuously with different loads (pumps, fans, compressors, conveyers, etc) [2]. The significant loss reduction in steady-state and transient modes may be obtained for these drives. Another example is multi-motor drive with mechanical link where the proper load distribution results in loss minimization.

The second area is related with changes in technology with respect to development of more efficiency control of mechanism speed. In this case the consumed energy of drive is reduced. These are the drives of HVAC-installations, reciprocating pumps and compressors, conveyors, fuel/air ratio control systems, etc. The main idea is the replacement of constant speed drive by variable speed drive and more complicated automation related with use of closed-loop control of pressure, flow, temperature, etc). The technological parameters that were not adjusted or were adjusted not efficiently are involved in control process.
In many cases energy saving comes along with water or fuel saving. The feature of both mentioned approaches is the reduction of energy consumed by a drive. The losses are reduced in first case while the more efficient drive technology is used in second case.

Note that a certain project should include analysis of different ways of energy saving. So the complex approach to energy saving task is required for maximum efficiency obtaining. Let us consider some of energy efficiency increase methods listed above related with hoisting gear applications.

At present, there are three prevalent types of induction motor drives basically used in hoisting gear applications:

- constant speed drives based on squirrel-cage motors;
- drives based on multi-speed squirrel-cage motors with several windings;
- variable speed drives based on slipring motors and switchgear control system.

However, there is an up-to-date trend of FCD application for these machines. Let us consider the main advantages of FCD and take example by crane drives and elevator drive.

2 Gantry Container Crane

To illustrate the features of crane drives we consider the gantry container crane for railway containers of IC and ICC type with load carrying capacity 20 T. The survey of the crane was carried out with use of energy consumption analyzer AR5 and brought out the following disadvantages of electrical equipment:

- the crane drives are based on slipring motors and resistors in rotor circuit. Step switching of rotor resistors is an outdated control method and does not provide satisfactory control quality and smooth motion. This results in high wear of the crane construction;
- the rotor resistance control is not efficient at reduced speed and can't be considered as advisable control method;
- the switchgear control results in high wear of electrical equipment at intermittent duty;
- the reactive power consumption is rather significant in this drive structure, the power factor is equal 0.5–0.6.

Application of FCD provides the following advantages:

- smooth and step free speed control in all range;
- smooth acceleration and braking significantly increase the reliability of mechanical and electrical equipment, prolong its life time and improve comfort of crane control;
- high quality vector control;
operation without or with minimum reactive power consumption;

energy saving caused by high-efficient type of control in all speed range and minimization of acceleration losses;

the elimination of switchgear operation in power circuit resulting in higher reliability of electrical equipment;

the great number of parameters available for commissioning, monitoring and visualization.

There are two possible cases of FCD application with use of semiconductor frequency converters.

First case is the traditional double-bridge frequency converters containing diode rectifier and IGBT-inverter. The additional braking units and braking resistors are used for absorption of regenerated energy in braking modes. This solution is related with significant increase of equipment dimensions and with relatively low efficiency. Every converter requires a commutating reactor, a braking unit, a contactor and a circuit breaker. The rated powers of converters are selected to withstand the 220–250% overload of rated motor current.

In second case the regenerative-rectifier units supplying the individual inverters for each motor with common DC link are used. The main advantage of this solution is the possibility of return of energy to supply network in braking modes. This feature allows eliminating of large racks with braking resistors. Each motor is fed by its own individual inverter converting the DC voltage of common DC link to AC voltage with variable frequency and amplitude. The use of individual inverters instead of parallel motor connection allows using of high-quality vector control, makes it possible to equalize the loads and speeds of several motors and provides the reservation due to possibility of operating with one inverter disabled. The rated powers of inverters are selected to withstand the 220–250% overload of rated motor current.

The traditional solution for regenerative drive is related with use of double-bridge thyristor rectifier, but the up-to-date converters are built on the base of active rectifiers. The active rectifier usually has the same construction and power circuit as an inverter, but has the other control algorithm. The repeatability of construction allows using the common spare parts for inverters and active rectifiers. The active rectifiers have the following advantages:

• no commutation faults when the power fails even in regenerative operation;

• almost pure sinusoidal line currents and voltages;

• for line supplies with significant voltage fluctuations, the DC link voltage level, which can be parameterized, can be kept constant;

• extremely high drive dynamic performance due to stable control of DC link voltage even with fast load changes of the drives;
- operation without reactive power consumption or with selected power factor (even capacitive);
- common spare parts, interfaces, operator panels with inverters.

![Bar chart showing energy consumption of different types of crane drives](image)

**Figure 1: Energy consumption of different types of crane drives**

The calculations carried out with use of mathematical simulation have shown that FCD based on squirrel-cage motor in compare with switchgear rotor resistance control drive based on slipring motor provides reduction of losses almost in all operating conditions. The acceleration losses can be reduced in 5-10 times with frequency-controlled starting. The steady-state losses at reduced speed are decreased proportionally to relative speed. The losses of braking lowering of a load can be reduced in 15-20 times. The elimination of negative-sequence braking allows reducing the braking losses in 2-3 times. The most efficient drive system for cranes could be built with use of frequency converters with active rectifiers. Energy consumption for hoisting unit drive and travel unit drive at 40% duty and 120 starts per hour is shown in Figure 1. The 100% energy consumption corresponds the switchgear-controlled drives. The calculations carried out with use of the program simulation block for energy consumption [3] show that the most efficient application of FCD is the hoist drives. The energy saving for them may reach 60-80%. Generally, energy consumption of whole crane may be reduced in two times. It is important to note that use of frequency converters and flexible PLC control provides the higher level of equipment reliability, smooth motion, automatic stabilization of load, equalization of parallel motors' torques, higher safety etc.
3 Passenger Elevator

Recently, the stable trend of FCD application in elevators occurs. This trend is explained by the fact that FCD significantly improves the comfort features of elevator operation due to effective limitation of accelerations and spurs. The smooth transients provide the significant reduction of dynamic stresses in kinematic elements. This results in elimination of often repairs or replacement of gearboxes, rope driving pulleys, chocks, motors and elements of counterbalance drop. But the main reason of FCD application in elevators is the 40–60% reduction of energy consumption mainly due to reduction of drive inertia (removing the acceleration limiting flyer).

Figure 2: Simulation results for the elevator FCD:

a – double-speed based motor drive, b – frequency-controlled drive
The frequency converters application allows using of standard single-speed induction motors. The rotor inertia of such motors is rather low in compare with double-speed motors. Moreover, their cost is less in 3-4 times.

To estimate possible energy saving in elevator drives the simulation of its operation was carried out for old double-speed drive and new frequency-controlled drive.

The Figure 2 shows the results of calculations for the 400 kg elevator (V=0.71 m/s; 120 starts per hour, 60% duty, 10% duty at low speed and 50% duty at high speed). It's clear from Figure 2 that transients in a double-speed elevator are related with significant dynamic stresses. The starting impact torque reaches the 580% value in compare with the rated high-speed torque. The switching to low speed is also related with impact torque – 260% in compare with rated low-speed torque. The dynamic torques result in high degree of wear of kinematic gear. The periodical replacement of equipment is required in this case. The table 1 shows the technical data of elevators with different types of drives that were used in simulation:

Table 1: Technical data of elevators with different types of drives used in simulation

<table>
<thead>
<tr>
<th>Electric drive</th>
<th>Switchgear double-speed</th>
<th>Frequency-controlled</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor type</td>
<td>AHP180SA6/24</td>
<td>4A100L6Y3</td>
</tr>
<tr>
<td>Rated power, kW</td>
<td>3.0/1.0</td>
<td>2.2</td>
</tr>
<tr>
<td>Rated current, A</td>
<td>9.0/14.5</td>
<td>5.6</td>
</tr>
<tr>
<td>Motor inertia, kg·m²</td>
<td>0.156</td>
<td>0.013</td>
</tr>
<tr>
<td>Inertia of additional rotating elements, kg·m²</td>
<td>0.94</td>
<td>0.083</td>
</tr>
<tr>
<td>Inertia of headway elements, referred to motor shaft, kg·m²</td>
<td>0.063</td>
<td>0.063</td>
</tr>
<tr>
<td>Total inertia referred to motor shaft, kg·m²</td>
<td>1.159</td>
<td>0.176</td>
</tr>
</tbody>
</table>

The results of energy consumption calculations based on transients described above [3] are shown in Table 2 and Figure 3.

The energy consumption per hour for the elevator with FCD reduced by 40% in compare with traditional switchgear double-speed drive. Considering that the elevator operates 6.8 hour daily, the saved energy is equal 5.1 kWh daily and 1879 kWh annually.

The efficiency of FCD application consists of energy saving and maintenance cost reduction. The period of repayment is estimated as 3–8 years depending on load carrying capacity and duty. The less term corresponds the higher carrying capacity and duty. The FCD for considered elevator would pay off in 6.4 years. It is acceptable term because the standard lifetime for this unit is 25 years.
Table 2: Results of energy consumption calculations based on transients

<table>
<thead>
<tr>
<th>Electric drive</th>
<th>Switchgear double-speed</th>
<th>Frequency-controlled</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy consumption per hour W, kW·h</td>
<td>1.898</td>
<td>1.141</td>
</tr>
<tr>
<td>Total losses per hour $\Delta W_M$, kW·h</td>
<td>1.02</td>
<td>0.24</td>
</tr>
<tr>
<td>Stator losses per hour $\Delta W_{M1}$, kW·h</td>
<td>0.43</td>
<td>0.16</td>
</tr>
<tr>
<td>Rotor losses per hour $\Delta W_{M2}$, kW·h</td>
<td>0.59</td>
<td>0.08</td>
</tr>
<tr>
<td>Efficiency, %</td>
<td>46</td>
<td>79</td>
</tr>
</tbody>
</table>

Figure 3: Energy consumption of different types of elevator drives

4 Conclusion

The calculations carried out with use of the program simulation block for energy consumption [3] show that implementation of FCD allows obtaining the significant energy saving effect in different hoisting gear application.

Thus, the application of FCD based on squirrel-cage induction motors instead of switchgear resistor control provides the reduction of energy losses almost in all operating conditions of crane drives.

In elevator drives energy consumption can be reduced by 40–60%. This effect is determined mainly by the possibility of significant reduction of drive inertia.
The less significant results in terms of energy saving can be obtained in conveyer and transporter drives. However, the important technological advantages could be reached due to smooth start and braking (cargo care) and speed control (coordination of transport flows, bin level control, etc). These advantages result in growth of productivity and product quality.

5 References


Using MATLAB Simulink for Energy Consumption Calculation of Induction Motor Drives

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Abstract

The paper deals with development of program block for estimation of energy consumption by induction motor drive. The block is created in MATLAB / Simulink application. The block topology, parameter-setting window and equations used in block are shown. The proposed method used in drive simulation allows estimating consumed energy, energy losses and energy efficiency of different drive systems. The calculation results with using developed block at different induction motor control methods are illustrated.

1 Introduction

The using of frequency-controlled drives in various industrial applications becomes the standard solution nowadays. This trend is caused by many reasons including the energy consumption reduction related with implementation of such drives. The task of efficiency estimation for different drive topologies should be solved in these cases. This task is relatively simple for Heating, Ventilation, and Air Conditioning (HVAC) applications, but becomes not trivial for drives with cyclic loads. Obviously, that the task of quantitative comparative energy consumption estimation for different induction motor drive system is appeared to prove cost efficiency of frequency-controlled electric drives application. Let us consider energy consumption principles with using Simulink application in MATLAB environment. Application of proposed principles during induction motor drive simulation of concrete mechanism allow to estimate consumed energy, electric losses in stator and rotor, i.e. energy efficiency for modern induction motor drive can be estimated. Besides the technical and economic assessment the energy consumption calculation principles can be used for heating test a chosen induction motor by averages losses method. The solving of mentioned tasks simplifies a designing procedure of induction motor drive systems.

2 Target setting

The purpose of this work is to develop program block for estimation of energy consumption by induction motor drive. The block is created in MATLAB / Simulink application. The block topology, parameter-setting window and equations used in block are shown in fig.1. The proposed method used in drive simulation allows estimating consumed energy, energy losses and energy efficiency of different drive systems.
The developed program block solves the following tasks:

- Calculation of consumed energy for necessary time period ($W_1$) and for any type of load and duty cycle.
- Calculation of energy losses ($\Delta W$) in these operation modes.
- Calculation of electric losses in stator ($\Delta W_1$).
- Calculation of electric losses in rotor ($\Delta W_2$).
- Calculation of mechanical energy ($W_m$).
- Calculation of efficiency for duty cycle, instantaneous losses and average losses.

Iron losses, ventilation losses and additional losses were not taken into account because their influence on total losses is negligible, especially for drives with cyclic loads.

Figure 1: Structure and parameters determination window of energy consumption block in Simulink Toolbox

During the developing of energy estimation block taking into account that to divide a stator and rotor losses a stator resistance is used and it may be changed in some cases (for example in double-speed induction motor during the switching on high-speed winding).

Also it is necessary to take into account that the block will be used for energy calculation of controlled-velocity electric drive, a mathematical model of induction motor drive may be written in per unit system, so the block equations are changed. These changes are described below.

It’s evident that the estimation block should be connected with models of drive topologies. The block can operate with models based on any reference frame ($x$-$y$, $d$-$q$, $\alpha$-$\beta$) with actual or referred units. The proposed method was used for investigation of energy efficiency in many industrial applications with frequency-controlled drives.
3 The building of consumed energy and losses calculation block

As mentioned above, the expression for active power is changed if per unit system is used. Therefore two variant of building energy consumption calculation block are considered.

3.1 The building of consumed energy and losses calculation block in physical units system

In this case the equations for energy consumption calculation block are following:

Mechanical output on induction motor shaft:

\[ P_{mec} = M \cdot \omega, \]

where \( M \) and \( \omega \) – electromagnetic torque and angular velocity of induction motor.

Active power consumed from the mains supply:

\[ P_1 = \frac{3}{2} \cdot (U_{sx} I_{sx} + U_{sy} I_{sy}), \]

where \( I_{sx}, I_{sy}, U_{sx}, U_{sy} \) – stator current and voltage vector projection in rotating frame.

Active power balance without taking account iron losses:

\[ P_1 = P_{mec} + \Delta P_1 + \Delta P_2. \]

Induction motor windings copper losses from the active power balance:

\[ \Delta P = P_1 - P_{mec}. \]

Electric losses in stator are determined by means of active stator resistance and stator current vector projections in rotating frame.

\[ \Delta P_1 = R_1 (I_{sx}^2 + I_{sy}^2), \]

where \( R_1 \) – stator circuits resistance.

Electric losses in rotor circuits:

\[ \Delta P_2 = \Delta P - \Delta P_1. \]

Active energy consumed from the mains supply:

\[ W_1 = \frac{T_{ct}}{} \int P_1 dt, \]

where \( T_{ct} \) – cycle time of machinery work.
Copper loss energy:

\[ \Delta W = \int_0^{T_{ct}} (P_1 - P_{mec}) \, dt. \]

Cyclorama efficiency is defined as relation mechanical output energy to Active power energy consumed from the mains supply during the cycle time.

\[ \eta = \frac{W_{mec}}{W_1} = \frac{\int_0^{T_{ct}} P_{mec} \, dt}{\int_0^{T_{ct}} P_1 \, dt}. \]

### 3.2 The building of consumed energy and losses calculation block in per unit system

In this work oriented on stator circuit variable and electromagnetic power of induction motor per unit system is used [1]. It allows to find referenced stator circuit variables and referenced electromagnetic torque equal to unity.

In this case only the equation for active power consumed from power supply is changed [1]. And it is necessary to introduce a base power to find a energy in per unit system.

Active power consumed from the mains supply:

\[ p_1 = ( u_{sx} i_{sx} + u_{sy} i_{sy} ). \]

Block topology based on equations showed above is depicted on fig.1. To eliminate dividing on zero in start of simulation constant equal to 0,01 is introduced in block topology. It is not influence on simulation results accuracy.

### 4 Simulation results

Let us consider an example of crane wound-rotor induction motor MTM412-6 simulation under different control method. Rated power of wound-rotor induction motor MTM412-6 is 22 kilowatt. Typical cyclorama to be operated is depicted on fig. 2.

To calculate energy consumption a requested cyclorama and load diagram of static torque, rated date of induction motor, equivalent moment of inertia is set. Furthermore, it is necessary to set either number of cycling on per hour or cycle time. In example induction motor works with rated static torque equal to 218,9 N·m on all segment of cyclorama. Equivalent moment of inertia takes equal to 3,27 kf·m². It is 1,21 from the rated moment of inertia of induction motor. Number of cycling on per hour was taken
equal to 60 cycling on per hour thus cycle time equal to 60 seconds. Low speed takes
equal to 0.3 from the synchronous speed of induction motor.

Figure 2: Typical cyclorama with low speed level

The followings control methods are considered:

1. Field-oriented induction motor vector control system with rotor field orientation [3].
2. Scalar control with stator resistance voltage drop correction on low speeds [3].
3. Resistance control of induction motor [4].
4. Phase control based on "thyristor voltage converter induction motor" (TVC-IM) system [5,7].

In all case except resistance control series resistance in induction motor rotor is not
introduced. In the case of resistance control rotor resistance smoothly changed to pro-
vide properly work of drive system according to typical cyclorama depicted on fig.2.

Transients according to drive systems mentioned above showed on fig.3. Mechanical
energy required for work by typical cyclorama staid constant for all control method and
equal to 2,15 kilowatt-hour.

Calculation results of consumed energy and losses under work on typical cyclorama
leads to table 1.

One must mention that the rated induction motor torque and synchronous speed of
induction motor are used as a reference torque and speed.

Besides the calculation of consumed energy the development program in Simulink ap-
plication allow to illustrate transients of comparable drive systems (fig. 3).
Table 1: Consumed energy and losses for different type induction motor control methods under work by typical cyclorama

<table>
<thead>
<tr>
<th>Energy, kilowatt-hour.</th>
<th>Vector control</th>
<th>Scalar control</th>
<th>Resistance control</th>
<th>Phase control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Consumed energy, $W_1$</td>
<td>2,54</td>
<td>2,96</td>
<td>3,4</td>
<td>4,41</td>
</tr>
<tr>
<td>Cooper energy losses, $\Delta W$</td>
<td>0,39</td>
<td>0,81</td>
<td>1,25</td>
<td>2,26</td>
</tr>
<tr>
<td>Electric losses in stator, $\Delta W_1$</td>
<td>0,24</td>
<td>0,47</td>
<td>0,24</td>
<td>1,29</td>
</tr>
<tr>
<td>Electric losses in rotor, $\Delta W_2$</td>
<td>0,16</td>
<td>0,34</td>
<td>1,01</td>
<td>0,98</td>
</tr>
<tr>
<td>Efficiency $\eta$, %</td>
<td>0,85</td>
<td>0,73</td>
<td>0,63</td>
<td>0,49</td>
</tr>
<tr>
<td>Mechanical energy, $W_{mec}$</td>
<td></td>
<td></td>
<td></td>
<td>2,15</td>
</tr>
</tbody>
</table>

Figure 3: Transients under work by typical cyclorama
1 – induction motor torque in per unit system,
2 – induction motor angular speed in per unit system:
a.) – Vector control, b.) – Scalar control, c.) – Resistance control, d.) – Phase control
To illustrate obtained results a diagram is depicted on Figure 4, where consumed energy and losses showed in kilowatt-hour. As can be seen from example, using energy consumption calculation block allow taking enough full date for technical and economic assessment to introduce an efficient drive system.

In addition mathematical models of comparable drive system was developed to estimate energy consumption. Using development block reduce a calculation procedure of energy consumption since it is not require an additional time study from the designer.

One must mention that this block can be used for heating test a chosen induction motor by averages losses method.

5 Conclusion

The calculation of energy consumption allows to choose one of mentioned above drive systems from energy efficiency point of view. Besides it can to carry out comparative quantity appraisal of energy consumption for different induction motor drive systems. Thus it enables to calculate technical and economic assessment for different drive systems and determinate pay-back period during introduction of modern drive system, especially, frequency-controlled electric drives [6,7,8].
Table 2: List of symbols

<table>
<thead>
<tr>
<th>Meaning</th>
<th>Notation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Consumed energy</td>
<td>$W_1$</td>
</tr>
<tr>
<td>Cooper energy losses</td>
<td>$\Delta W$</td>
</tr>
<tr>
<td>Electric losses in stator winding</td>
<td>$\Delta W_1$</td>
</tr>
<tr>
<td>Electric losses in rotor winding</td>
<td>$\Delta W_2$</td>
</tr>
<tr>
<td>Mechanical energy</td>
<td>$W_{mec}$</td>
</tr>
<tr>
<td>Efficiency</td>
<td>$\eta$</td>
</tr>
<tr>
<td>Active power consumed from the mains supply</td>
<td>$P_1$</td>
</tr>
<tr>
<td>Copper losses power of induction motor windings</td>
<td>$\Delta P$</td>
</tr>
<tr>
<td>Electric losses power in stator winding</td>
<td>$\Delta P_1$</td>
</tr>
<tr>
<td>Electric losses power in rotor winding</td>
<td>$\Delta P_2$</td>
</tr>
<tr>
<td>Mechanical output on induction motor shaft</td>
<td>$P_{mec}$</td>
</tr>
<tr>
<td>Stator circuits resistance</td>
<td>$R_1$</td>
</tr>
<tr>
<td>Cycle time of machinery work</td>
<td>$T_{ct}$</td>
</tr>
<tr>
<td>Stator current projections in rotating frame</td>
<td>$I_{sx}$, $I_{sy}$</td>
</tr>
<tr>
<td>Stator voltage vector projection in rotating frame</td>
<td>$U_{sx}$, $U_{sy}$</td>
</tr>
<tr>
<td>Reference angular induction motor speed</td>
<td>$\omega^<em>$$^</em>$</td>
</tr>
</tbody>
</table>

6 References

Taking Full Advantage of Potential Energy Savings with a New Concept of Speed Control for Centrifugal Pumps

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Dipl. Ing. Marjan Silovic, KSB Aktiengesellschaft, Frankenthal, Germany

Abstract

As any life cycle cost analysis shows, energy tends to take the largest share in the cost of running a centrifugal pump. However, by controlling the speed of asynchronous motors, up to 60% of the electric power can be saved, in individual cases even more. Today, the speed of asynchronous motors is normally controlled by an electronic frequency inverter. Although these are available in many types and sizes, they are not used on centrifugal pumps on a wide scale. The reasons for this are the unawareness among users of the potential savings speed control can offer, as well as the lack of attractive technical solutions. When looking at technical solutions, a basic distinction has to be made between newly installed pumps and the upgrading of pumps already in service.

Most frequency inverters on the market today are designed for separate mounting in a control cabinet. These normally stand in a separate room at some distance from the pumps. The electrical connection to the motor is by means of a shielded cable to avoid interference to other electronic devices (EMC protection). Whereas this aspect can be considered from the start when planning a new installation, it tends to be more complex and very costly on existing pump units. As the frequency inverters sold are multi-purpose – or in other words designed for a great variety of applications - they are not easy to operate. To take full advantage of the energy saving potential offered by a centrifugal pump, one should know all the ins and outs of a pump's running properties.

To be able to correctly set the parameters of a frequency inverter for a centrifugal pump to operate at the point of best efficiency, users have to have a thorough knowledge of the complex processes involved in, for example, heating or cooling circuits, pressure boosting and waste water disposal systems.

Our insight in the best possible operation of centrifugal pumps in a wide range of applications acquired in many decades has culminated in a new approach to problem-solving. The new solution has a modular design which is based on a standardized hard- and software platform. It enables the simple adaptation, both mechanically speaking and from an electrical/electronic viewpoint, to the application in question, irrespective of whether that involves a new installation or is part of upgrading an older pump unit.

It eliminates the drawbacks of today's solutions and is totally independent of the place of installation or mounting. The new application-related software makes for an optimal, energy-efficient operation of the pump. In the future, centrifugal pumps can be provided with speed control in all applications where this makes sense. Lastly, the new type of speed control offers a number of additional protective and diagnostic functions. The users need no other automation components to run their centrifugal pump system efficiently and reliably. Quoting several practical examples, the authors demonstrate the benefits of the new speed control concept.

1 Introduction

Pumps are an important part within processes, where liquids have to be transported. Pumps and pumping systems need a large amount of electrical energy, which is consumed in industry applications. Therefore since several years there are various activities to reduce life cycle costs of pumps and pumping systems.

As any life cycle cost analysis shows, energy tends to take the largest share in the cost of running a centrifugal pump (Fig. 1).
To reduce life cycle cost, we first have to look at the largest pie, the energy consumption. Centrifugal pumps are driven by asynchronous motors. Using high efficiency motors is already one step to reduce energy consumption of asynchronous motors. But there is another aspect where we can find an even larger potential for savings in life cycle cost (LCC) of centrifugal pumps, especially with regard to energy expenses: it can be achieved by controlling the speed of the pump. Today, the speed of asynchronous motors is normally controlled by an electronic frequency inverter. By controlling the speed of asynchronous motors of centrifugal pumps by frequency inverters, up to 60% of the electric power can be saved, in individual cases even more (Fig. 2).
Although these frequency inverters are available in many types and sizes, they are not used on centrifugal pumps on a wide scale. The reasons for this are the unawareness among users of the potential savings speed control can offer, as well as the lack of attractive technical solutions. When looking at technical solutions, a basic distinction has to be made between newly installed pumps and the upgrading of pumps already in service.

2 User requirements

Among the users of pumps and pumping systems there is already a growing trend toward focusing on their own core competences. To find out exactly what they expected from the automation of centrifugal pumps and pumping systems, in this case, what characteristics a frequency inverter must have in order to be more often used in pump applications, we are in close contact to several major users / operators of such pumps and systems.

The following customer needs and buying arguments emerged from the contacts:

- Best possible performance of the pumping duty
- Compliance with all requirements regarding quality, reliability, environmental protection, industrial safety and health
- High availability
- Minimum life cycle costs
- Smoothest possible integration of equipment into the overall installation

At the end of the round of talks, we held a list of requirements for the frequency inverters and their features. Some are listed below:

- Integration of drives and frequency inverters
- Reduction in planning, assembling, installation, commissioning and maintenance costs
- Innovative service concepts.
- Higher electrical and mechanical efficiencies, lower control- and low load-operation losses
- All-in solutions to simplify the required planning, installation, handling and service scopes
- Simplicity of adjustment to changing operating conditions
- Systems must be suitable for retrofitting on installed pump population

The total list of requirements served as a reference for the development of a new concept for the efficient automation of centrifugal pumps and pumping systems. The first step was to create an automation concept for centrifugal pumps. A product family concept for pump automation was the result (Fig. 3).
3 The platform concept

To be suitable for a host of different processes, installations and systems, automation solutions have to be very adaptive. It, therefore, takes a great variety of products to meet customer needs quickly and flexibly. If product costs are to be kept within reasonable limits while offering the whole spectrum of options required, a strict variants management is absolutely indispensable. One possibility of meeting this challenge is to opt for modular product families, i.e., to create platforms (Fig. 4). These can then be taken as a basis for the configuration of the required products and their variants. Standardized hardware and software platforms for the desired automation scope will help shorten the time-to-market considerably. This does away with the need for developing new products from scratch, because they can be configured from the modules making up the product family.

Figure 4: Basic idea of the modular concept
The use of standardized parts additionally leads to a substantial drop in manufacturing costs.

With the aid of METUS (Management Tool for Unified Systems, Dr. Jan Göpfert, id-consult München), a tool used in the automobile industry, we have defined and implemented platforms for automation- and drive - products.

As a first step, the method calls for an analysis of all the requirements to be met by an automation platform and all the functions it is expected to perform. The maximum scope of functions thus obtained is then grouped according to several detailing levels in line with the customer’s needs. The next step is to examine how the different requirements can be realized. Part of this step is to determine which variants are required. After structuring all functions and variants, the required number of platforms is defined on the basis of the so-called scenario method. To complete the process, all necessary modules of the platform are described and developed. The result of this methodical approach is now available to our company in form of an automation and a drive platform. All products needed to control, monitor, diagnose, drive and operate pumps and valves are based on the modules of these two platforms. These modular units and the products created from them provide numerous options for designing flexible systems that will make fluid transport more efficient. For one, various modules are interchangeable, thus allowing product upgrades, as well as enabling communication across systems. By adopting and using platforms, we have been able to create standardized, user-oriented signalling and operating interfaces ("Look & Feel"). That, in turn, served as a basis for the "Plug and Run" approach developed for commissioning and operation. Through cuts in the expenditure for training and product literature, other business units, like Sales and Service, also benefit from this development.

4 The Platform-based variable speed solution

The continuously variable speed adjustment of commonly used asynchronous motors is realized by using the tried and tested principle of the electronic frequency inverter. Many devices sold today have been developed for a wide variety of applications. That is, they are not specifically designed for use with a centrifugal pump. This often calls for complicated and time-consuming parameterization. To make matters worse, many installations employ a host of independent monitoring, diagnostic and speed control systems, which in turn make use of different communication channels and can only be combined at considerable cost.

With the introduction of a new product family for driving pumps, we launched the first products of a novel, platform-based speed control solution in April 2005. The product is a platform based, modular, self-cooling frequency inverter, specially designed for pump applications.

Based on a standard frequency inverter, the new platform offers pre-parameterized modules for a wide range of pump applications and types which provide for easy commissioning and optimum speed control.
That means the product offers all the benefits generally associated with variable speed systems. Additionally pump specific functions are integrated, which improve pump operation drastically and therefore increase system availability and process quality. Because of its modular concept in hard- and software the product solution can be used in various applications like

- Cooling systems
- Filters
- Water supply systems
- Heating, ventilation and air-conditioning systems
- Irrigation
- Boiler feed circuits
- Steam generation
- Process circuits
- Cooling lubricant supply systems
- Service water supply systems
- Industrial processes.

Some selected basic functions which are special for centrifugal pump applications are

- Motor protection function like
  - Dynamic overload protection by speed limitation
  - Electrical motor protection by over- / under voltage monitoring
  - Thermal motor protection by PTC thermistors

- Basic pump automation functions
  - Closed loop operation via integrated, adjustable PI controller
- Automatic sensor recognition
- Dynamic pressure compensation

- Slave in multipump configuration with up to 6 pumps

Additional functions in the Advanced model allow to use it also as a master in multipump systems. Some selected, pump special functions are

- Pump protective functions
  - Characteristic curve control (Qmin, Qmax)
  - Minimum flow stop
  - Dry running protection without external sensor

The product is equally suitable for integration in motors, wall mounting or mounting in a control cabinet because of its modular housing and mounting concept (Fig. 6).

This also makes for easy retrofitting. The available designs for wall mounting up to 110 kW and the other for integration in a control cabinet, the product covers all installation variants employed today with a single standardized system. It can even be used for synchronous or electronically commutated (EC) motors.

The realized solution – comprising a motor with an integrated frequency inverter and a power range from 0.55 to 45 kW – will be used to automatically control the pressure, flow rate, a given fluid level or the temperature. Efficient protective devices, such as for example EMC filters to class A/B, dry running protection and tripping if the flow rate falls below a minimum value offer maximum operating reliability. The drive can be integrated in existing automation systems by means of digital interfaces. A number of communication modules and a common operation philosophy will allow its effective combination with other units like monitoring and diagnostic systems, while providing a less experienced user with a reliable and easy-to-use tool. A modular plug-in LON or Profibus interface is used to transfer information about vital operating conditions of the
drive as well as process data to the process control system by means of a suitably designed data transmission network.

Up to six drives can be operated in parallel in a master / slave configuration. If the master fails or malfunctions, one of the other drives assumes the role of master. A fast programming function allows the process to be optimized in terms of speed, change of sense of rotation, start-up of an additional peak load pump, PI controller dynamics and pipe friction loss compensation. An automatic restart after automatic safety tripping helps reduce downtimes to a minimum while providing maximum safety by the product itself. A consistent user interface and technical platform for easy integration into process control systems help reduce commissioning and maintenance costs for different types and other automation products (Fig. 7).

Figure 7: Structural diagram of a multi pump application

Figure 8: Application example of a heating circuit with master and slave
5 Summary and outlook

The requirements to be met by pumping systems in terms of reliability, safety, environmental compatibility, sustainability and availability will continue to increase. However, instead of accepting a cost increase to meet the higher demands, users insist that life cycle costs go down. Faced with these opposing needs, we started developing system platforms which are also used as drive platforms. All are designed for use with a broad range of applications and pump series without significantly increasing production, storage or processing costs. Users benefit from the modular design of the systems. Upgrades or retrofits can be effected at any time. This means: Devices are no longer assigned single functions; they leave the user free to monitor only those parameters that are essential to the process involved. In the next few years, we expect to see new business or financing models and innovative service packages becoming established. As a basis for these innovations, we are presently developing smart, interactive platform systems that will make for lasting changes in the world of pumps as we know it today. The described concept shows that still improvements are possible to reduce energy consumption and therefore life cycle costs of centrifugal pumps and systems.
A Larger Motor/Converter Combination for Higher Efficiency Drives

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Abstract

The brushless doubly fed machine (BDFM) has been proposed for many years as a variable speed drive machine, where the converter does not need to be of equal rating to the motor.

The advent of modern, compact Voltage-Fed PWM Converters with flux vector control suggests that such converters could be combined with BDFM technology to achieve a larger rating integrated drive than has been possible with current Integrated Induction Motor/Converters.

This paper describes a prototype Integrated BDFM Motor/Converter of 4 & 8 pole technology rated at 11 kW implemented from proprietary components but using an advanced BDFM rotor design. Simulations have predicted its performance and tests are presented to characterise the potential of the drive. The paper shows the speed range possible from the drive and the limitations to its performance from power factor and the parameters of the machine.

1 Introduction

Improving motor efficiency requires a detailed understanding of motor magnetic & conductor losses, needing detailed investigation and design optimisation of the machine, as has been described in previous EEMODS Conferences, for example for induction motors by Caselotti et al 1999 and Tavner et al 2002.

An important alternative route to energy saving is through driven-load applications, by operating motors at variable speed. Recent technology has incorporated the variable speed converter with the induction motor for a wide range of small motor applications as an Integrated Induction Motor/Converter. The units currently available on the market range in output from 0.1-7.5 kW, see Figure 1, limited by the thermal rating and size of the Converter which can be mounted on the Motor.

This paper presents a different approach, combining a new type of motor, the Brushless Doubly Fed Machine (BDFM), with a reduced size Converter as an Integrated BDFM Motor/Converter, allowing larger, 4-20 kW, drives to be targeted.

The benefit is that a wider power range of energy-intensive processes, in air-conditioning, air-handling and liquid-processing, could be targeted for the compact application of energy-efficient variable speed technology.

The penalty of such an arrangement will be that the Integrated BDFM Motor/Converter achieves a smaller speed range, will operate at a lower power factor and the motor design is subject to some rating restrictions.
This paper presents the results of a prototype Integrated BDFM Motor/Converter demonstrating its performance in comparison to theory and considering the consequences of this technology in an integrated drive.

Figure 1: Example of a typical Industrial Integrated Induction Motor/Converter, with a 1.1 kW Converter mounted on a 1.1 kW, D90 Motor, courtesy of Danfoss

Figure 2: Photograph of the prototype Integrated BDFM Motor/Converter considered in this paper, with a 7.5 kW Converter mounted on an 11 kW, D160 Motor, 10x the rating of Figure 1, courtesy of Marello Motori

2 Motor & Converter

The motor in this paper is a conventional, proprietary, 2 winding, 2-speed, 11 kW induction motor fitted with a modified rotor, enabling it to operate as a BDFM. A photograph of the prototype arrangement is shown in Figure 2. The motor has two sets of stator windings, 4 pole and 8 pole with a closed 6 pole wound rotor designed to ensure BDFM action with details as follows:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frame centre height</td>
<td>D160</td>
</tr>
<tr>
<td>Stator &amp; rotor core length</td>
<td>190mm</td>
</tr>
<tr>
<td>Stator bore diameter</td>
<td>155mm</td>
</tr>
<tr>
<td>Stator winding 1</td>
<td>4 pole, rated power 11 kW, 0.8 pf, &amp; flux 12.9 mWb</td>
</tr>
<tr>
<td>Stator winding 2</td>
<td>8 pole, rated power 1.4 kW, 0.6 pf, &amp; flux 3.97 mWb</td>
</tr>
<tr>
<td>Stator Voltage &amp; Connection</td>
<td>400 Vrms (line), 50 Hz, delta connected</td>
</tr>
<tr>
<td>Air gap</td>
<td>0.40 mm</td>
</tr>
<tr>
<td>Rotor outer diameter</td>
<td>154.2mm</td>
</tr>
<tr>
<td>Rotor winding</td>
<td>Novel design of 6 progressively wound two-layer loops</td>
</tr>
</tbody>
</table>


The Converter is a conventional, proprietary, single-quadrant, voltage fed, 7.5 kW PWM converter with flux vector control. There is one 50 Hz mains power supply, which is split inside the Converter. One circuit is fed direct to the 8 pole motor Power Winding and the other is fed, via the Converter, to the 4 pole Control Winding. The converter is mounted on the back of the motor, like the Integrated Induction Motor/Converter described above, the difference will be that in this case the Motor/Converter combination will be larger and the power rating available correspondingly greater. The arrangement of Motor and Converter is shown in Figure 3.

![Diagram of the arrangement of the BDFM](image)

Figure 3: Diagram of the arrangement of the BDFM, taken from Roberts 2004

This cascade technology has been described by Broadway 1970, Boger et al 1996, Williamson 1997 & Roberts, 2004, amongst others, but has received negligible application in small-size drives. The evolution of BDFM technology is exemplified by Figure 4.

![Evolution of Integrated BDFM Motor/Converter](image)

Figure 4: Evolution of Integrated BDFM Motor/Converter from Integrated Induction Motor/Converter
3 Simulation & Performance

The modelling of this type of machine is complex but a finite element time-stepping method has been developed by Jagiela et al 2005, which has been tested on a machine described by Roberts et al 2004, similar to the machine presented here.

Figure 4: Photograph of the rotor showing the 6 pole, two layer, BDFM winding

Figure 5: Predicted FE flux plot for the BDFM motor, using the method of Jagiela et al 2005

Figure 6: Simplified equivalent circuit taken from Roberts et al 2004

Figure 4 shows a rotor with the winding design used in the Integrated BDFM Motor/Converter.

In the test series, described by Roberts et al 2004, the machine was operated in pure induction or self-cascade mode, with one stator winding fed and the other short-circuitied. Tests were performed at a reduced supply voltage of 90 Vrms, to limit stator currents to acceptable values and ensure all results were obtained at the same flux. The applied voltage gave a nominal airgap flux density throughout the tests of about 0.125 Trms. Individual torque measurements were obtained at steady state and Roberts et al used these results to extract the parameters of the equivalent circuit, Figure 6, of the machine enabling performance predictions.
In the time-stepping, finite element simulation a linearly increasing speed of 800 rev/min/s was applied to the rotor shaft. The simulation was repeated twice for the rotor, each stator winding being short-circuited separately. The simulation also used 90 Vrms, 50 Hz phase voltage.

The simulations produced full transient flux plot sequences but these cannot be presented here. Figure 5 shows the final fully-developed magnetic flux plot for the rotor in Figure 4. Figure 7 shows the transient speed, torque and current waveforms, from startup at zero speed to four-pole cascade operation. Plotted on these curves are the Torque-Speed characteristics measured by Roberts et al 2004. In cascade operation the simulation results are in good agreement with test data.

Any discrepancy is mainly due to the short period of simulation, whereas the test results were obtained in steady-state. Some oscillations in the current and torque waveforms were observed at eight-pole cascade operation, four-pole winding short-circuited, as a result of the relatively high rate of change of speed imposed on the rotor during simulation.

The flux plot reveals that the flux pattern in the rotor is controlled by the 6 pole winding of the rotor but flux is restricted in this rotor core because the rotor slots were deep, to accommodate the requisite copper cross-section. This was taken into account in the
design for the rotor of the Integrated BDFM Motor/Converter as the pitched, double-layer winding was used but the rotor yoke depth was increased over that for the rotor shown in Figures 4 & 5.

The simulations show good agreement with measurement, giving confidence in the method developed by Jagiela et al 2005.

The performance of the BDFM is subject to considerable investigation and is not intended to be the subject of this paper, the objective of which is to demonstrate that this emerging technology can be applied to larger-size, Integrated Motor/Converter combinations, to achieve energy-saving for a wider range of driven-load applications.

However, an important conclusion of the simulation is that the development of the air gap flux pattern is dependent on the form of the rotor winding and the work has shown that the machine performance can be predicted using the equivalent circuit and flux plotting tools now to hand.

4 Testing

The Test Rig for the Integrated BDFM Motor/Converter described in this paper is shown in Figure 8. Following the test experience described by Roberts et al 2004, 2005, the Integrated BDFM Motor/Converter was tested first in Cascade, to elicit the characteristics of the rotor, which determine the performance of the drive. The cascade performance of the 4 pole and 8 pole windings is shown in Figure 9, which can be compared with Figure 7, where the rotor exhibits classic BDFM action.

![Test Rig for the Integrated BDFM Motor/Converter](image)

Figure 8: Test Rig for the Integrated BDFM Motor/Converter
The machine was then tested in BDFM mode. The BDFM develops both induction and synchronous torques but its performance and control is that of a synchronous machine, as described by Williamson et al 1997 and Roberts et al 2004.

![Cascade characteristics of the 4 pole and 8 pole windings of the Integrated BDFM Motor/Converter](image)

**Figure 9:** Cascade characteristics of the 4 pole and 8 pole windings of the Integrated BDFM Motor/Converter

![No load characteristic of the Integrated BDFM Motor/Converter, with 8 pole Mains-fed, 4 pole Converter-fed with improved flux boost.](image)

**Figure 10:** No load characteristic of the Integrated BDFM Motor/Converter, with 8 pole Mains-fed, 4 pole Converter-fed with improved flux boost.
Figure 10 shows the no-load BDFM performance of the machine, showing the reduced speed range available compared to that for a conventional Induction Motor/Converter with 4 poles on 50 Hz. Figure 10 also shows that the power factor on the Power & Control windings varies over the speed range. This has an important bearing on the motor performance on-load because it suggests that the kVA demand of the Power & Control winding circuits will change with rotor load. Testing of the prototype is continuing with load and efficiency tests which will be presented at the Conference.

5 Discussion

These preliminary tests have shown that an Integrated BDFM Motor/Converter can be configured to operate as a BDFM over a useful speed range, more restricted than that of a conventional Integrated Induction Motor/Converter. The use of a smaller rated Converter has enabled the integrated approach to be applied to a larger motor enabling a higher-powered Integrated BDFM Motor/Converter than would have been possible with a conventional Integrated Induction Motor/Converter.

The BDFM has some similarity to the now extinct AC Commutator machine but a closer affinity to the Doubly Fed Induction Motor, with the rotor excitation fed across the air gap rather than through slip rings, incurring a magnetization current penalty.

The work of Roberts et al 2004 has shown that the BDFM performance is heavily dependent on the effect of the two magnetization arms in the equivalent circuit Figure 6. The power factor of the supply to the Power & Control windings depends upon the machine load and these parameters. These power factors determine the relative ratings of the Power and Control Windings and of the Converter. It is clear from the preliminary tests that these power factors can be low and the design of the machine needs to reflect this by having as short an air gap as possible. The equivalent circuit work of Roberts et al 2004 has also shown that the rotor resistance must be as low as is practicably possible, consistent with achieving an acceptable rotor magnetic circuit.

Converter control not only affects the speed of the drive but the balance of power between the Power and Control circuits, consistent with the rating and parameters of those circuits. It has been clear from these experiments that conventional converter control will not be adequate to control the synchronous behaviour of the Integrated BDFM Motor/Converter.

The approximate cost of a single 7.5 kW Integrated Induction Motor/Converter, of a form like Fig 1, will be approximately Euro 750. The cost of an 11 kW Induction Motor and separate Converter will be approximately Euro 2500. The cost of the Integrated BDFM Motor/Converter, along the lines described in this paper, could be Euro 2000, giving a 20% saving, depending on the machine rating and manufacturing costs associated with the BDFM rotor.
6 Conclusions

- An Integrated Motor Drive of power rating, 11 kW, larger than current Industrial Integrated Motor Drives has been implemented using BDFM 4 & 8 pole technology. The larger rating is achieved because the Converter is only partially rated to the Motor.

- A useful operational speed range of 150-950 rev/min of the Integrated Motor Drive has been demonstrated. That speed range is restricted compared to that possible for a conventional Integrated Drive of 4 pole & 50 Hz, 0-1500 rev/min, and depends upon the rating of the Converter, the pole configuration of the BDFM and the relative ratings of the BDFM stator windings.

- A time-stepping, finite element simulation has accurately represented the complex flux pattern of the machine, there being good agreement between the torque-speed predictions of the simulation and the measured cascade torques on a prototype machine.

- The power factor of the supply to the Power & Control windings of the Motor depends upon the machine load and parameters. These power factors determine the relative ratings of the Power and Control Windings and of the Converter. It is clear from the preliminary tests that these power factors can be low.

- The BDFM Motor should be designed to have as short an air gap as is practicable and the rotor resistance should be as low as possible, consistent with achieving an acceptable rotor circuit.

- The conventional control of the Converter is not adequate to provide stable control of the BDFM in its synchronous mode of operation and this will be the subject of further work.

- The Integrated BDFM Motor/Converter could be achieved with a capital saving of approximately 20% depending on the machine rating and manufacturing costs associated with the BDFM rotor.

7 Acknowledgements

The authors acknowledge the prior work of colleagues at Cambridge University on the prototype BDFM, their helpful cooperation and the assistance of Marelli Motori SpA and Laurence, Scott & Electromotors Ltd for the provision of this prototype motor and the fabrication of the rotor.

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Brazilian Industrial Energy Efficiency Program: Focus on Sustainability

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Abstract

This paper presents the achievements and goals of the Industrial Motor System Optimization Project as developed by the PROCEL INDÚSTRIA – Brazilian Energy Efficiency Industrial Program, within the scope of PROCEL – National Program for Electric Power Conservation, carried out ELETROBRÁS since 1985.

Its main objective is to minimize losses in the motor driven systems already installed in the Brazilian industry.

In order to implement this program, ELETROBRÁS is continuous making agreements with the state industry federations aiming to develop mechanisms and to manage energy efficiency implementation projects looking forward its self supporting.

PROCEL INDÚSTRIA aims to reduce the waste of electric energy in the industrial sector, to increase the industries competition, by reducing their costs and to contribute to the preservation and cleaness of environment.

1 Introduction

The genesis of the project occurred at the time of the electric power supply crisis in the middle of 2001, with the Federal Government instituting the Energy Power Crisis Management Chamber (GCE) for the purpose of preparing a Strategic Plan for Emergency Electric Power Supply. In addition to the implementation of medium and long-term actions, this was aimed at increasing electric power supply to ensure meeting the full demand for power, with reduced risks of load shedding, thereby preventing losses to the population, economic growth constraints and undesirable impacts on employment and income.

Within this context the Motor System Optimization Project was conceived, given its capability to obtain effective energy conservation results in the short and medium term, in addition to its being suitable for incorporation into a National Energy Policy and taking into account its innovating nature based on structured dissemination and self-sustainability actions.

This paper presents the peculiarities of this project which makes it innovative and highly important, in that it leverages the industrial sector by making it more competitive in reducing its specific consumption through the efficient use of energy.

Therefore, the fundamental aspects related to the importance of the Optimization of Motor-Driven Systems in the Brazilian national energy matrix are presented below,
describing in detail the efforts under the Project for attaining the planned goals and the several actions already performed. This includes the supplemental efforts developed with the Universities in setting up laboratories and supporting the preparation of master’s and doctoral theses on the topic “Optimization of Motor-Driven Systems”.

2 Industrial Motor System Optimization Project

2.1 Importance of Motor-Driven Systems

The consumption of electric power by the industrial sector represents 45.5% of the total consumption in Brazil, as reported by ELETROBRAS’ Energy and Market Studies Department – DEM, for 2004 (see Figure 1). Despite the weight of the power intensive industries in such overall consumption, the motor-driven systems are the greatest power waste villains in the other industrial segments, topping the 80% figure in the textile and paper and pulp industries.

![Electric Power Consumption in 2004](image)

Figure 1: Distribution of Electric Power Consumption in Brazil

According to data from the latest Useful Energy Balance (BEU), motor-driven systems represent about 49% of the electric power consumed in the industrial sector, as shown by Figure 2.
In (4), the preponderance of the electric power costs is clear in relation to the total costs of energy inputs for most industrial segments. The costs pertaining to electric power consumption in driving power are singled out as the principal components of such costs. Therefore, besides presenting a great potential for reducing consumption, we can affirm that this project likewise offers a reduction in energy input costs, which is directly reflected on company profitability.

2.2 Project Objectives

One of the project objectives is to minimize losses in motor-driven systems already installed in the Brazilian industry.

To this effect, PROCEL INDÚSTRIA has been developing joint efforts through agreements between ELETROBRÁS and the State Federations of Industries and Universities, with a view of implementing energy efficiency measures in the entire national territory.

The second project objective is to expedite the market penetration of high efficiency three-phase induction motors, pursuing the goal of increasing such percentage to around 30%. The use of such motors is a very attractive alternative from a technical-economic viewpoint, considering that the reduction of technical losses promotes a substantial reduction of the energy consumed along their estimated useful life of 15 years.

2.3 Project Goals

Around 74.4% of total motor load in industry concerning power are composed of ventilation, compression and pumping systems.

Studies conducted by PROCEL have identified a number of energy conservation opportunities, such as, in motor-load coupling, motor oversizing, and using electronic motor drives (ASD), among others. Energy audits performed by Brazilian Electric Energy
Research Center (CEPEL) on compressed-air systems of industries have indicated an energy conservation potential above 20% without the need for large investments, through a decrease in the level of system losses. Pursuing this goal is justified in view of the widely varying operating efficiency of motor-driven systems, ranging from 15% to 80%.

Taking as reference the 15% potential for energy savings as identified in the United States, the potential for annual energy savings in Brazil is around 6.0 TWh. For this estimate, it was considered that the 2,000 largest Brazilian industries consume about 58 TWh, with 70% of this total being in ventilation, pumping, and compression systems, and the correspondent total potential for savings is 15%. On this basis, it is expected that this project implementation in 2,000 establishments will provide energy savings of 2 TWh.

2.4 Detailing of Project - Methodology

The Program dynamics to attain the goal of 2 billion kWh in losses reduction consists in getting industries committed to the implementation of the energy efficiency measures identified by their own agents, who have been trained on a gratuitous basis by multipliers suitably prepared by ELETROBRÁS/ PROCEL under a multidiscipline course of 176 hours duration in Optimization of Motor-Driven Systems.

In support of these actions carried out with industries directly involved, the Program sets up Motor System laboratories for teaching purposes under agreements with Universities, and finances scholarships for development of undergraduate and graduate papers addressing the topic of “Energy Efficiency of Industrial Motor-Driven Systems”.

The actions for energy efficiency under this Project, developed through agreements with the State Federations of Industries, are distributed into four works, as detailed below:

2.5 Entrepreneurs Awareness in Target Industrial Sectors, and Training Multipliers with an expertise in Industrial Motor System Optimization

This work starts with the federation preparing a sectoral study, by industry and subsector, addressing the percentage of electric power consumption due to motor-driven systems. This defines the companies to be invited into a awareness plan about the economic advantages of participating in the project.

From that point on, activities are started to make industries’ corporate governance aware of the importance of implementing energy efficiency measures for their industrial plants’ motor-driven systems, and to obtain industries’ commitment to participating in PROCEL INDÚSTRIA Program.
In parallel to such awareness action, multipliers selected from among university teachers and consultants experts are trained through a course with 176 hours duration, as shown in table 1, administered by a group of instructors and specialists indicated by ELETROBRÁS, having recognized competence and experience in motor system optimization.

Due to the fact that the optimization of a motor-driven system is a complex matter involving the combination of knowledges that are separately provided in the process of educating Brazilian engineers, the training course for multipliers in Optimization of Motor-Driven Systems, with the multidisciplinary approach offered in its formatting, is intended to minimize the strong knowledge barrier that perpetuates itself in the existing education structure of industries’ professional staff.

The programmatic content of the Multiplier Training Course includes such disciplines as Electric Power Feed System, Electric Motors, Electronic Adjustable Speed Drive, Pumps, Economic Analysis of Investments, Compressors, Fans and Exhaust Fans, Conveyor Belts, Motor-Load Coupling, Instrumentation and Control, Oriented Pedagogy, Marketing and Sales of Projects, Energy Audit Methodology for Motor-Driven Systems, Industrial Safety, Case Study and Technical Visit.

2.6 Skills Building for Industries’ Agents, and Measures Implementation

At this stage, the knowledge acquired by the multipliers is transferred to industries’ representatives, making them prepared to develop energy audits in their manufacturing plants, indicate solutions, assess the implementation costs of recommended measures and the financial and electrical gains obtained, with a view to reduce electricity consumption and costs without interfering with quality and production.

Subsequently, under the coordination of multipliers, industries’ agents proceed to implement the economically attractive energy-efficiency measures identified by themselves.

2.7 Setting Up Success Cases

During this phase, the Project participating industries which are more representative as regards the importance of motor-driven systems in their facilities are selected from among the targeted industrial sub sectors, mainly those industries committed to implementing the measures recommended by energy audits performed by organizations of recognized technical competence.

2.8 Monitoring, verification, and results divulging

During this stage, the evaluation and monitoring are performed of the process for implementing the energy efficiency project in the participating industries, as well as the
divulging of the implementation results of such project through a workshop aimed at the several sectors of state industries.

2.9 Project Support Activity – Laboratory Capacity Building

In support of these actions carried out directly with the industries, the Program sets up motor driven system laboratories for teaching purposes under agreements entered with universities, and finances scholarships for development of graduate and postgraduate papers addressing the topic “Energy Efficiency of Industrial Motor-Driven Systems”, thereby levering the activities of teaching and research on these systems.

<table>
<thead>
<tr>
<th>Course</th>
<th>Hourly load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric power concepts, Energy Quality and Tariffs</td>
<td>08</td>
</tr>
<tr>
<td>Electric Motor</td>
<td>16</td>
</tr>
<tr>
<td>Electronic Motor Drive</td>
<td>16</td>
</tr>
<tr>
<td>Pumps</td>
<td>16</td>
</tr>
<tr>
<td>Compressors</td>
<td>16</td>
</tr>
<tr>
<td>Fans and Exaust Fans</td>
<td>16</td>
</tr>
<tr>
<td>DB motor – Motor Energy Audit</td>
<td>04</td>
</tr>
<tr>
<td>Conveyor Belts; Motor &amp; Load Coupling</td>
<td>16</td>
</tr>
<tr>
<td>Instrumentation and Control</td>
<td>08</td>
</tr>
<tr>
<td>Economic Analysis of Investments</td>
<td>08</td>
</tr>
<tr>
<td>Industrial Safety</td>
<td>08</td>
</tr>
<tr>
<td>Monitoring &amp;Targeting</td>
<td>08</td>
</tr>
<tr>
<td>Energy Audit Methodology for Motor-Driven Systems</td>
<td>08</td>
</tr>
<tr>
<td>Technical Visit/ Energy Assessment and Case Study - First Part</td>
<td>08</td>
</tr>
<tr>
<td>Case Study - Second Part</td>
<td>04</td>
</tr>
<tr>
<td>Oriented Pedagogy/ Marketing &amp; Project Sales</td>
<td>16</td>
</tr>
</tbody>
</table>

Such laboratories will serve as a meeting point for discussion and research in electrical, civil, production, and mechanical engineering, thus contributing to engineers’ education with the multidisciplinary skills required by the physical nature of motor-driven systems. This is a manner of pursuing the perenniality of Procel Industria’s actions, in that it works toward the education of new engineers and brings closer together teachers of the different engineering disciplines.
2.10 Description

These agreements, with 3 years duration, are intended to promote the technical-financial cooperation between Eletrobrás and the Universities for procurement of equipment to be used in Motor System Laboratories for teaching purposes, where the aspects relating to Energy Efficiency by industrial consumers can be assessed.

Each laboratory contemplates the installation of 4 complete motor-driven systems, standalone and automated, allowing varying the operating conditions of such equipment as centrifugal pumps, air compressors, fans and conveyor belts. Such aspects as the use of standard and high efficient motors, frequency inverters and motor & load coupling, among others, can be compared and assessed from an energy efficiency point of view, so as to present the operating characteristics of each motor/load system and its interaction with the electric system feeding it. Through sensors for measuring the electrical and mechanical parameters, it will be possible the real time monitoring of the electromechanical characteristics of each test, store them in a database and issue reports to support analyses, studies and development of academic papers.

2.11 Goals

As a result, the energy efficiency concepts are expected to be disseminated in the academic and industrial circles, thus adding up the multidisciplinary knowledge already existing in the universities in order to prepare the relevant design and technical specifications and coordinate the setting-up, operation and maintenance of the Laboratory; create minimum energy efficiency indices for the implemented systems; assess the opportunities for energy savings on such systems; offer extension courses, consultancy and lectures; getting professionals trained in the appropriate skills needed to develop and provide consultancy on energy efficiency; assess the potential for energy conservation in motor-driven systems installed in each State; and develop 7 graduate and 3 postgraduate papers on industrial motor-driven systems.

3 Project Results

At present, agreements are under way with the main State Federations of Industries in the five geographic regions of Brazil, with the results shown in Table 2 below.

Significant responsiveness and integration have been perceived among the several entities participating in the program, which allows us to count on results beyond the original expectations.

Table 3 shows the number of scholarships granted under the project. This action is expected to provide the technical strengthening of higher engineering education in Brazil, considering that the multipliers are university teachers, and the trend that the acquired multidisciplinary knowledge and experiences will be reflected on new disciplines, new researches and greater integration among the several engineering branches.
Table 2: Summary Table of Project Activities by State

<table>
<thead>
<tr>
<th>Region/ state</th>
<th>Skills building for multipliers</th>
<th>Trained agents</th>
<th>Planned self-audits</th>
<th>N.º of participant industries (forecast)</th>
<th>Principal sectors</th>
</tr>
</thead>
<tbody>
<tr>
<td>North</td>
<td>10</td>
<td>155</td>
<td>120</td>
<td>70</td>
<td>Beverages, Two Wheels, Electronica, Metallurgy and Plastics</td>
</tr>
<tr>
<td>Amazonas</td>
<td>10</td>
<td>155</td>
<td>100</td>
<td>50</td>
<td>Food and Beverages, Mineral Extraction and Processing, Metallurgy, Fisheries, Paper and Plastics, Soap and Oils, Timber and Furniture</td>
</tr>
<tr>
<td>Pará</td>
<td></td>
<td>20</td>
<td>20</td>
<td></td>
<td>Food and Beverages, Mineral Extraction and Processing, Metallurgy, Fisheries, Paper and Plastics, Soap and Oils, Timber and Furniture</td>
</tr>
<tr>
<td>Northeast</td>
<td>43</td>
<td>274</td>
<td>320</td>
<td>246</td>
<td>Textile Products, Food and Beverages, Nonmetal Mineral Products and Leather Preparation and Making of Travel Articles and Footwear</td>
</tr>
<tr>
<td>Ceará</td>
<td>10</td>
<td>172</td>
<td>100</td>
<td>66</td>
<td>Food Products, Chemistry and Nonmetal Mineral Products</td>
</tr>
<tr>
<td>Pernambuco</td>
<td>15</td>
<td>26</td>
<td>100</td>
<td>80</td>
<td>Chemical/Petrochemical/ Refining, Metallurgy, Food/Beverages &amp; Paper/Pulp</td>
</tr>
<tr>
<td>Bahia</td>
<td>18</td>
<td>76</td>
<td>120</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>Midwest</td>
<td>35</td>
<td>359</td>
<td>200</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>Mato Grosso</td>
<td>18</td>
<td>359</td>
<td>100</td>
<td>50</td>
<td>Timber, Food &amp; Nonmetal minerals</td>
</tr>
<tr>
<td>Mato Grosso do Sul</td>
<td>17</td>
<td>0</td>
<td>100</td>
<td>50</td>
<td>Cold storage, soy crushers &amp; tanneries</td>
</tr>
<tr>
<td>South-east</td>
<td>17</td>
<td>42</td>
<td>300</td>
<td>250</td>
<td></td>
</tr>
<tr>
<td>Minas Gerais</td>
<td>17</td>
<td>42</td>
<td>300</td>
<td>150</td>
<td>Food, Foundry, Textile, Mining, Electronica, Metallurgy &amp; Steel-making</td>
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<tr>
<td>São Paulo</td>
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<td></td>
<td></td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>South</td>
<td>18</td>
<td>457</td>
<td>200</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>Santa Catarina</td>
<td>18</td>
<td>76</td>
<td>200</td>
<td>100</td>
<td>Food, Textile &amp; Paper/ Pulp</td>
</tr>
<tr>
<td>Total</td>
<td>123</td>
<td>906</td>
<td>1.140</td>
<td>766</td>
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</table>
Table 3: Scholarships offered to project partner universities

<table>
<thead>
<tr>
<th>Region</th>
<th>Universities</th>
<th>Scholarships</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Bachelor's</td>
</tr>
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<td>North</td>
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<td>21</td>
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<td></td>
<td>UTAM</td>
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<tr>
<td></td>
<td>UFAM</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>UFPA</td>
<td>7</td>
</tr>
<tr>
<td>Northeast</td>
<td></td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>UFC</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>UFPE</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>UFBA</td>
<td>7</td>
</tr>
<tr>
<td>Midwest</td>
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<td>21</td>
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<tr>
<td></td>
<td>UFMT</td>
<td>7</td>
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<tr>
<td></td>
<td>CEFET-MT</td>
<td>7</td>
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<tr>
<td></td>
<td>UFMS</td>
<td>7</td>
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<tr>
<td>Southeast</td>
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<td>105</td>
</tr>
<tr>
<td></td>
<td>UFU</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>UFSJ</td>
<td>7</td>
</tr>
<tr>
<td>South</td>
<td></td>
<td>91</td>
</tr>
<tr>
<td></td>
<td>UDESC</td>
<td>7</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>84</td>
</tr>
</tbody>
</table>

4 Conclusion

The significant participation of federations of industries from the principal Brazilian states demonstrates the consistency of the actions being implemented under PROCEL INDÚSTRIA Program as well as the approval of the industrial consumer, who now perceives the project as an opportunity to reduce costs and increase competitiveness. In addition, this project brings along actions that seek to perpetuate the interest for efficiency, working to integrate this area into the priorities of the local industrial culture, becoming part of the industries’ entrepreneurial strategy. Two actions are quite important in this respect: (1) promoting the technical strengthening of Brazilian engineering through scholarships and laboratories for teaching and applied research purposes, and (2) inducing the federations’ creation of energy efficiency nuclei for rendering services to the state industrial community through a network involving Eletrobrás-accredited multipliers, agents in the industry, universities, and energy savings companies (ES-COs). The innovating nature of operation which seeks to minimize losses in the complete motor-driven system, involving motor, load, coupling and the process of production, and to enhance systems already installed is filling a knowledge and an approach gap until then inexistent in the market.
5 Bibliographic References


Motor System Audit
and Software Tools I
Energy Efficiency Assessment PC Calculator for Flow Machines

Akseli Savolainen, M.Sc., ABB Oy, Drives, FIN-00381 Helsinki, Ph: +358 5033 23709, Fax: +358 1022 22287, e-mail akseli.savolainen@fi.abb.com

Abstract

The paper describes a PC calculator software tool, developed at ABB for estimating energy efficiency of flow machines (i.e., pumps and fans) and especially their driving power arrangements. The software tool is able to calculate power and energy consumption of a fan or a pump at different operating points, with several different flow control methods. The control methods covered include throttling valve (pump), throttling damper (fan), inlet vanes (fan), on/off control, hydraulic coupling, voltage control, and AC drive (frequency converter / inverter). Induction motors with different efficiencies can be compared. The tool also can differentiate between common fan and impeller types, but they cannot be compared as alternatives to each other.

The user of the software tool first creates a model of the existing flow machines and their drive & control arrangements. Then, several improvement actions can be selected. These fall into two main categories: 1) equipment efficiency improvements and 2) control method improvements. The tool examines then the energy savings these actions would bring.

Energy auditors may find the software useful, because it allows for several pumps and fans to be studied in one calculation project. The savings from individual improvement actions are added together, and as an end result the tool returns the total energy and money saving achievable in a plant’s electric motor–driven pump and fan systems.

To reliably being able to estimate the energy consumption of any common motor driven pump or fan, there has to be a general-purpose model of its power requirements and losses in different operating conditions. In real life situations, the data available relating to an installed pump or fan and its drive may be limited. The mechanical power requirement of a pump or fan may not be known, and the power losses within different drive train arrangements are difficult to estimate for all necessary flow rates. Hence, an empiric loss model, which gets by on limited initial data, was developed for the purpose.

The paper explains how the software tool handles the above mentioned situations and what the calculations are based on.

1 Introduction

A well-known fact for the professional audience is that the majority of all electricity consumption in industrial operations is by the electric motor. Several approaches to improve the energy efficiency in these motor-driven systems exist, from improving the efficiencies of the individual system components to more system-level approaches where also the operating and maintenance practices are accounted for. Many calculation tools are provided by manufacturers and governmental agencies for calculating energy savings, which could be achieved by improving the component efficiencies in the system or the way it is being used. These tools are typically targeted for only one purpose, i.e. for estimating the energy saving achievable by improving the efficiency of a component (motor upgrade) or a system improvement (control method upgrade), but not both at the same time. Moreover, often only one motor can be calculated, whereas there can be hundreds or even thousands of motors in an industrial plant. Thus, energy
auditors wishing to perform a plant-wide analysis for, say, pump and fan systems could be better equipped as far as calculation software is concerned.

Our objective at ABB drives and motors business units was to develop a site-level calculation software, which would assess the energy saving potential in terms of motor efficiency and control system improvement of the motor population at an industrial plant.

2 Assumptions and scope of calculation

This section briefly depicts the scope of calculations and the assumptions and limitations of the tool.

2.1 Applications

The motor applications targeted with this calculation tool are industrial pumps and fans, where the energy saving potential is at highest within motor-related electricity consumption in process industries (See Fig 1). It is assumed that the pumps and fans to be analyzed have been correctly dimensioned (i.e, they are being used as they are meant to).

Figure 1: Economic savings potential in industry. (EEMs=energy-efficient motors, VSDs=variable speed drives = AC drives).
2.2 Possible motor types

Typical induction motors are assumed. Name plate values are required, or instead; rated power, rotating speed and efficiency can be entered. The tool only needs to know the nominal efficiency figure for the motor, and manipulates it to suit also other operating cases than nominal.

Both IEC type and NEMA motors can be entered. The difference between them is that if the calculation tool takes the value for granted or not. A motor efficiency value per NEMA is considered to be more accurate.

2.3 Possible improvement actions

The energy saving calculation is based on an “existing” and “improved” drive system for each pump or fan. Improvement may refer to:

- Motor efficiency upgrade (example: eff3 -> eff1)
- Control method upgrade (example: throttling control of a pump -> speed control with an AC drive)
- AC drive upgrade (an old AC drive -> new AC drive)

3 The structure of the calculation tool

A typical use case of the calculation tool is described in the following. An energy auditor might be performing an energy analysis for the pumps and fans of a chemical factory.

The tool’s user interface is made of three “tabs”:

1. General information
2. Calculations
3. Results

General information is for entering and saving reference and identification data related to the calculation project in question. On the Calculations tab, the actual (or fictional) drive systems in place are specified and various improvements to them can be selected. Results tab is for presenting the aggregated results from all the comparisons made.

Of these, this paper mainly discusses Calculations tab and gives justifications for the calculations made.

3.1 Initial data needed – pump case

When studying a pump installation, for instance, the pump and the system where it operates have to be specified. A pump is specified by entering its nominal flow, nominal head, maximum head and rated efficiency, see Fig. 2 below.
Based on the pump data entered, a default pump curve is assumed and exhibited. Also system curve is of default shape, but the intersection of the two is the pump’s nominal operating point. The system curve starts from the head value corresponding to the static head.

Figure 2: The modeling of the pump, the existing drive train, the operating profile and selecting the improvement actions takes place on this screen.

Lower half of the screen is dedicated for the drive system for the pump. A possible mechanical transmission or clutch is specified by giving its nominal efficiency. “Existing motor data” is for entering the name plate data of the motor. This is needed for calculating the efficiency of the motor because the value is not always readily available. But, if the efficiency is known, it can be entered directly, and the tool uses that figure as a starting point for loss calculations.

The last phase in modeling the existing drive system is to select the flow control method for the existing installation. In a pump case, the main alternatives are:

- Throttling control with a valve
- Bypass

---

1 The term “drive system” refers to a chain of equipment related to controlling (mechanical/electric), transforming (from electric to mechanical), and delivering motive power to a driven machine. A conventional drive system might include a hydraulic coupling and a motor, whereas a modern one might include a motor and an AC drive.
• Hydraulic coupling control
• Pump cycling (on/off)
• Voltage control (applicable for small unit size pumps)
• AC drive (frequency control)

With this data given, the pump with its existing drive train has been modeled in sufficient detail, in order to be able to estimate its power consumption in different operating points (flow points).

3.2 Fan case

If the motor application to be studied is a fan, the procedure differs somewhat. Possible fan types are:

• centrifugal
• axial, and
• mixed flow fan.

In case the fan is of centrifugal type, the type of its impeller should be selected. The alternatives are:

• forward curved
• radial
• backward curved impeller.

The fan type and its impeller type may have an effect on the power consumption characteristics, as can be seen from the Fig 3 below:

Figure 3: Relative power consumption of some fan types with various flow control methods.
3.3 Improvement actions

After the existing system has been modeled, the calculation tool allows for improvements to be done to the existing drive train system and finding out their effect on system efficiency and, ultimately, on the energy consumption.

For example, if the tool reveals the existing motor has a bad efficiency (eff3), the user can select the “Improved motor” option and gets a list of suitable ABB motors to select from. The efficiency value of the “new” motor appears automatically to the lower “motor data” box and the possible energy saving effect is seen in results.

Another possible upgrade would be to replace the conventional control method, say, a hydraulic coupling with an AC drive. In this case, the efficiency of the transmission part would improve, because one would get rid of the losses of the coupling. The lower “clutch” box would show 100% efficiency because a rigid, lossless coupling could be installed instead. A suitable AC drive type is to be selected from the list of recommended drives (control method/drive column, lower portion). The relevant data of the selected drive are shown and the energy saving figure updates automatically.

3.4 Operating profile

An essential piece of data in making energy calculations is the duration or the operating profile of the flow machine. Required data is the total annual operating time in hours. To find out how it is distributed across flow ranges, the flow area of the pump/fan has been divided into 9 segments. The number of hours falling into each flow segment is to be specified by the user.

3.5 Continuing the analysis

All the pumps and fans to be studied within one energy analysis can be entered in a similar way as described earlier. Each calculation of a motor/drive system appears as one row in the dropdown list of “calculations”, and can be revisited and edited later.

3.6 Results

The main outcome of the calculation software is the estimated energy saving to be achieved, if the selected improvement actions were taken onto the specified motor driven pumps and/or fans. By entering the prices of the needed equipment, the user of the calculation tool gets investment appraisal parameters such as the payback period for the improvements.
4 Calculations

4.1 Overview of the calculations

The main purpose of the software tool described herein is to calculate the energy saving potential, when old motors are being replaced with new ones, and traditional flow control methods in pumps and fans are replaced with speed control by AC drives. The energy saving figure is based on a comparison of “old” and “new” drive trains for the same pumps. Roughly, the calculation proceeds by the following steps:

- Calculate the power requirement of a pump/fan based on process values in the nominal point
- calculate the power requirement for different flow points (considering the flow control method)
- add coupling losses
- add motor losses
- Add losses of a possible control device (AC drive)
- Taking the operating profile into account, calculate the energy consumption
- Perform a similar calculation path for the “improved” system
- Compare => energy saving
- Environmental results such as CO₂ reduction (emission trading!)
- Enter cost data => economic results such as payback
- Many calculations as above all together => get summary of the results.

4.2 Empiric loss model of an induction motor

The energy saving calculations within the tool are based on estimating the losses in different components of the system in various operating conditions. Instead of using the so-called equivalent circuit method, sort of an empirical loss method has been developed for this purpose.

In this model, the nominal loss is assumed to be known. This can be calculated from the motor’s efficiency figure, or, if not given, using the motor’s nameplate values. The nominal loss is then broken into three components:

- basic losses (magnetization etc)
- speed dependent losses (friction)
- load-dependent losses

In the following formula for the motor loss with a sinusoidal supply voltage, all three components are present:
The graph below (Fig 4) demonstrates how well the formula above depicts the development of the relative losses in two examined induction motors as a function of the relative torque.

Figure 4: The relative losses of two induction motors and a loss curve depicted by a generic loss model (sinusoidal supply; frequency fixed at 50 Hz)

The graph reveals that the formula can predict the relative losses of the two measured motors with a substantial accuracy in all measured torque points except in one, which was the zero-torque point for a 15-kW test motor. But as this no-load operating point is of negligible importance at normal use, it can be concluded that the motor loss formula within the energy saving calculator seems to yield fairly accurate relative loss values in partial load operating situations.

If the motor is supplied from an AC drive, the voltage into the motor is not fully sinusoidal. In this case, a fourth component, harmonic loss, is needed within the loss model. It is commonly known that low switching frequencies in the output bridge of an inverter cause high harmonic content, causing extra losses and heating in the motor (mainly in the rotor). The higher the switching frequency, the lower the extra losses in the motor. Based on test results and literature (see Kinnares et all. 1999, Figs. 8 and 9), a formula has been composed for the extra, harmonic losses of an inverter-supplied motor. Once again, the formula is empiric of nature:

\[
P_{\text{loss\,sin}} = \left[ 0.20 + 0.1 \cdot \left( \frac{f}{f_{\text{nom}}} \right)^2 + \left( 0.45 \cdot \frac{T}{T_{\text{nom}}} + 0.25 \right) \frac{T}{T_{\text{nom}}} \right] \cdot P_{\text{nom\,loss}}
\]
\[ P_{\text{harm}} = \left( \frac{100}{f_{\text{sw}}} + 0.035 \right) \cdot P_{\text{nomloss}} \]

A comparison of the source measurements and the formula result are below in Fig 5.

![Graph showing harmonic loss in 7.5-kW motors as a function of switching frequency; components represented by different motors and equations used by ABB's energy calculation software.]

Finally, the total loss of an induction motor at any load and speed point in inverter duty can be reached by summing up the loss components just introduced:

\[ P_{\text{motorloss}} = P_{\text{loss sin} \theta} + P_{\text{harm}} \]

Using the methodology presented above, it is possible to estimate the total loss of an induction motor supplied from an inverter at any operating point, once the nominal loss (or efficiency) of the motor is known. This kind of loss modeling lays the foundation for credible energy saving calculations relating to induction motors and electric drives.

### 4.3 AC drive losses

Also the formulae for the losses of an AC drive (if installed) must account for the drive efficiency at the particular motor and drive loading. Loss equations derived in a similar manner as with motors are written inside the software, but as the efficiency curves of electric drives do not sink as much as with motors, this paper does not discuss these formulae further.
5 Conclusions

The new energy efficiency assessment tool, calculation software from ABB motors and drives, targets at overcoming many of the shortcomings of the existing energy efficiency calculators for electric motor drives systems. Ability to calculate many applications within one calculation project, possibility to assess the combined energy saving when upgrading the motor and replacing the old control method with AC drive control, improved calculation accuracy, support for both IEC and NEMA motors and both measurement units (metric and US), and the possibility to use default parameters for quick calculation are features that have been combined into one package. The tool uses an empiric model for fair calculation of motor losses at partial loading, in order to reach an acceptable accuracy level with limited initial data. Even though the tool recommends products from only one manufacturer as improvement actions, the versatility of ABB’s new energy savings calculation software makes it a useful tool for any energy auditor or plant engineer who is interested in the energy-efficient operation of pumps and fans in an industrial plant.

6 References

European Commission. Improving the Penetration of Energy-Efficient Motors and Drives. SAVE II Programme 2000

Simply Calculate the Cost-Saving Potential – A Computer Program Determines the Profitability of Energy-Saving Electric Drives

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When it comes to electric drive technology, by using suitable components – such as energy-saving motors or drive converters – just in Germany alone, billions of Euros of energy costs can be saved. The energy-saving potential for fluid flow and positive displacement machines such as pumps, fans and compressors is especially high – up to 50 percent.

Figure 1: Fluid flow and positive displacement machines such as pumps, fans and compressors have the highest energy-saving potential by using variable-speed operation.

A calculation program clearly highlights the energy-saving potential using specific plant parameters. The payback time of the components that are used is often just a few months.

Electric drive systems represent approximately 70 percent of the consumption of electric power in industry. In turn, a large percentage of this power is used for drive applications with square-law torque characteristics, such as pumps, fans and compressors.
that often only operate at partial load. The percentage of power costs in the overall operating costs of a medium-sized industrial pump is presently typically 46 percent and the trend is increasing. Similar values apply to all types of fans, pumps and compressors.

The reason for the high power consumption of many pumps, fans and compressors lies in the traditional control technique where the pumped medium is regulated using mechanical actuators such as throttles or bypass valves. The disadvantage of these techniques is that the motor always operates with the speed designed for the maximum pumped quantity. When the flow is throttled and at full speed – at the very best – it draws less active power. However, its efficiency and its power factor decrease. Under partial load operating conditions this means that energy is simply wasted.

1 Introduction - Up to 50 percent saving

On the other hand, variable-speed drive systems utilizing drive converters always precisely adapt the power they draw to the actual operating requirements. Put in another way – the motor only draws that power that is precisely necessary at the particular operating point. The result is a significantly lower power requirement than for fixed-speed drives with the same power rating that use mechanical control techniques in the partial load range.

Depending on the plant characteristics, this energy-saving can be up to 50 percent – whereby the energy-saving potential is especially high for steep plant characteristics.

Just in Germany alone, the energy-saving potential by using energy-efficient drive systems amounts to 20 TWh per annum. This corresponds to eight fossil fuel fired power station blocks with an emission of 11 million tons of CO₂ or – in hard currency - 1.5 billion Euros of energy costs.

2 Body of the paper

2.1 Background Up until now the potential has not been used

A significant proportion of this enormous energy-saving potential has not been used especially because the benefits of drive converter systems are not being consequentially used.

Presently, only about 5% of all of the motors used in industrial environments operate with electronic closed-loop speed control. From an energy and economic standpoint, a sensible percentage would be over 30 percent – and certainly the largest proportion of these for fan, pump and compressor drives. An important reason for the hesitation in using drive converters is the fact that in the planning phase there are only very rough estimates of what drive converters can actually save in terms of energy and the resulting pay-back time. This is the reason that frequently just the investment costs alone
mean that drive converters are not used, while costs incurred in operation – for energy, service & maintenance - are just considered to be secondary issues.

2.2 Scope - The plant parameters form the basis

Computer-based “energy-saving programs” available up until now were only conditionally suitable as decision-making basis. Generally, when calculating the energy-saving potential, these programs use the drive power. However, in the early planning phases, only application-specific parameters such as pumped quantity or delivery head are known that are decisive when selecting the drive concept. Generally there is also no possibility of comparing all of the alternative concepts – the efficiency of the components and the impact of the closed-loop speed control on the power factor, service & maintenance costs and plant lifetime are not taken into account.

![Figure 2: The program calculates the energy saving based on the plant-specific parameters such as flow, delivery head, pump profile and number of working days.](image)

2.3 Method - Comparison with all of the alternative concepts

In order to provide users in the process industry a sensible basis to calculate energy-saving potential, the new “SinaSave®” program from Siemens Automation & Drives no longer uses the drive system parameters, but those of the plant itself. This represents a
significant change. The plant-specific parameters such as the values required for the process are used as basis. These include the flow and delivery head for pumps and the mass flow and total pressure differential for fans, the density of the pumped medium and if known, the power rating of the selected pump, fan or compressor as well as its efficiency. The electrical efficiency and the total efficiency of the plant are also included in the calculation. The number of working days and working shifts as well as the pump profile, over the day and the year, that is decisive for the extent of the energy-saving impact are also taken into account. The higher the proportion of partial load operation in the pump profile, the greater the energy wastage when using mechanical control components.

Depending on the requirements, the user goes to the menu through the industry sector (e.g. chemical, water/wastewater, cement) or directly through the application. Here the user can select pumps, fans or compressors. In the main menu, the user enters the data of his particular plant. Thanks to the flexible program structure it is also possible to just enter part of the fields. Initially, the program selects the drive system with the matching power rating and price of a suitable drive converter from the basic data of the particular plant that has been entered.

Figure 3: The energy requirement of variable-speed systems can be compared with all of the usual alternative control concepts. In addition to the energy saving, additional positive effects when drive converters are use are taken into account.
In an additional step, the program determines the energy requirement of the variable-speed system for the specific application. It compares this with the values of all of the alternative concepts that have been considered for the particular plant. These include for example throttle valves, bypass, variable inlet vane or pole-changing motors. The energy saving is obtained from the difference between the calculated energy requirement of a variable-speed system and that of an alternative concept. The result is output as a numerical value. It is also visualized in the form of characteristics specific for the application that was entered. The program then converts the energy saving specified in kilowatt-hours into hard cash using the energy prices that actually apply for the particular plant.

![Energy saving program](image)

Figure 4: In addition to numerical values, the program visualizes the different energy requirement using plant-specific characteristics.

### 2.4 Results - Additional cost-reducing effects taken into account

This energy-saving analysis also takes into account cost-reducing effects of variable-speed drives that go beyond the decisive energy-saving effect. In addition to eliminating the mechanical control, these other factors include improved power factor and process control, lower stress on the motor and reduced service & maintenance for the driven load.

As a result of soft starting and stopping, variable-speed operation reduces the stress on the complete mechanical transmission line and also avoids unfavorable operating
states. These states include effects such as cavitation, gas being pumped along with the pumped medium, pressure surges and vibrations that can also damage the plant or system. For instance, by slightly shifting the motor speed, cavitation bubbles can be eliminated that can erode pump impellers. Further, associated areas of gas in the pumped medium that can interrupt the flow can be broken-up and ultrasonic compression surges that are typical for compressors and can stress the plant are prevented. Specific pump speeds can be suppressed to eliminate vibration.

The program calculates the payback time of the variable-speed system from the total monthly saving as a result of variable-speed operation and the purchase price of the drive converter. The energy-saving potential generally lies between 30 and 50 percent which means that the payback time for the drive converter is often just a few months. Operating companies can simply reap the economic benefit after this payback time.

3 Conclusion – a payback time of just a few months

This is clearly shown in an example where the program uses the power data for a water tower. Regional water companies use water towers such as these to generate water pressure. The water tower itself would be filled with pump drives utilizing power at a cheap nighttime tariff. The water tower is emptied during the day. The system data of the water tower is as follows:

**Application: Water tower without regulation**

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Figure 5: System data, water supply from a water tower.
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Figure 6: System data, water supply with water tower in SinaSave.

In this example, only the drives that are used to fill the water tower and to maintain the water supply are taken into account. Freshwater treatment processes were not taken into consideration.
The investment cannot be paid back. For a traditional water tower concept, it would not make sense to utilize a frequency converter. The water tower concept also has some significant disadvantages: These include the high investment and maintenance costs for the water tower itself and the risk that the water tower empties before the end of the day due to a high demand and must be pumped full using expensive electric power at daytime tariffs.

This is the reason that many water supply utilities are moving away from the water tower concept and are directly supplying users without using any water storage facility. Typical requirements for a direct supply concept are as follows:
Application: Water network with pipeline

<table>
<thead>
<tr>
<th>Duty Cycle</th>
<th>Requirements</th>
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<tbody>
<tr>
<td>80% 4h</td>
<td>H = 70 m</td>
</tr>
<tr>
<td>70% 4h</td>
<td>Q = 600 m³/h</td>
</tr>
<tr>
<td>60% 4h</td>
<td>n = 1450 1/min</td>
</tr>
<tr>
<td>50% 4h</td>
<td>Drive: SINAMICS G150, 400V</td>
</tr>
<tr>
<td>40% 4h</td>
<td></td>
</tr>
<tr>
<td>30% 4h</td>
<td></td>
</tr>
<tr>
<td>all over the year</td>
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</table>

Figure 9: Supply data, water supply without water tower

Contrary to the example above, it involves an enclosed system. The steady-state component of the delivery height is relatively high. This guarantees that the pressure in the supply network is maintained.
Figure 10: System data, water supply without water tower in SinaSave.

Figure 11: Alternative closed-loop control types and additional saving effects
For state-of-the-art direct supply concepts, it always makes economic sense to use frequency converters. When compared to conventional closed-loop throttle control, this investment has a payback time of just 13 months. Other cost savings complements this. These savings are as a result of the improved power factor, lower maintenance, lower load on the motor, improved closed-loop process control and the fact that the mechanical closed-loop control is eliminated.

In addition to using frequency converters to save energy, there are additional ways of significantly reducing the high energy consumption of electric drives.

The energy-saving impact of energy-saving motors can also be determined using a computer-based program – where, as result of mechanical design measures and optimized materials, the power loss of motors can be reduced by up to 45%. Further, a service can be offered where the energy-saving potential for all of the drives in the plant can be fully utilized.

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IMSSA: Creating an International Standard for Motor Software

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Abstract

The International Motor Selection and Savings Analysis (IMSSA) software tool was developed as a direct result of discussions at a previous EEMODS conference concerning methods to promote use of energy-efficiency motors. Building on experience with existing software, such as MotorMaster+ (U.S.) and Eurodeem (Europe), an international collaboration was formed to develop software that would provide a universal, flexible software shell adaptable for use in any country in any language. Through the support of the sponsoring organizations: Corporacion Nacional del Cobre de Chile (Codelco); the UK Action Energy (Carbon Trust), the European Community – JRC; Natural Resources Canada; the US Department of Energy; and the International Copper Association, IMSSA seeks to provide industrial users of motor systems with greater access to performance and decisionmaking information concerning energy efficient motors. In addition, the focus on international collaboration provides a unique environment for further dialogue on about the global harmonization of motor testing and energy efficiency standards.

This paper will examine 1) the process of developing the software by the sponsors in cooperation with Washington State University; 2) key features of the software, such as software shell flexibility and functionality, multiple databases, language and currency modules; 3) issues in creating and maintaining IMSSA for international use; 4) how the software can be used to support efficiency standards and labels; and 5) the sponsors’ experiences with launching the software in Canada, Chile, the United States, and Europe. A status report on new users of the software will be provided as well as plans to extend the use of the software to additional host countries and equipment manufacturers and distributors.

1 Introduction

The idea to develop international collaboration that would produce an international motor analysis and selection tool was put forward by Paul Scheihing, U.S. Department of Energy (USDOE); Dr. Hugh Falkner, from what is now UK Action Energy (formerly ETSU), and John R. Mollet, International Copper Association (ICA) at the 1999 EEMODS conference in London, UK. At this meeting, the principals identified an opportunity to work together to create an internationally-accepted software shell for motor analysis and selection that would provide both motor manufacturers and users of industrial electric motors with a common global platform for reporting and reviewing information concerning motor energy efficiency and related motor performance data. The primary purpose of this global platform is to encourage greater use of energy-efficient industrial electric motors and to increase the awareness of motor system efficiency worldwide. A secondary goal of international collaboration is greater communication concerning global variations in motor test standards for the purpose of promoting increased harmonization among those standards.
Motor systems account for a large fraction of the total energy consumption, for example, 60% of the US industrial electricity. On a global basis, industrial motor systems account for approximately 73% of all electricity used in manufacturing.\(^1\) Tremendous energy savings and emission reductions can be realized by selecting more energy-efficient motors and by following better motor system management practices.

At the time of project initiation, the global market offered motors rated with different test standards (Institute of Electrical and Electronic Engineers -IEEE, International Electrical Commission -IEC, Canadian Standards Association-CSA, the Japanese standard-JEC. Today, the CSA, JEC, and IEC test standards are either similar to IEEE or are being revised to achieve closer harmonization as a way to increase test accuracy, international trade and competitiveness. However, it is also a fact that most countries still apply the older IEC 34-2 test method for determining energy efficiency.

In an effort to promote greater use of energy efficient motors, the U.S. and the European Union had each developed motor-management software, MotorMaster+ and Eurodeem, respectively. Other motor selection tools had been developed in Chile, Mexico, Brazil, and Poland. But with the increasing globalization of the market for industrial motors, the project sponsors realized that the proliferation of individual tools might not be the best approach for this market. In addition, neither equipment providers nor users alone can bridge the inherent differences in standards, units, frequency, motor models, and utility structures among the different countries.

An international motor systems software tool was envisioned to address these issues. This software would be flexible enough to serve the needs of developing as well as developed countries. A further benefit of such a tool would be support for the ongoing process of standards harmonization. Collaborative development of the software would allow the participants to leverage funding and expertise to develop the best overall product accomplished with minimum resources.

### 2 Forming the Collaboration

To initiate the collaboration, a letter of intent and a project description were prepared in late 1999. The letter of intent invited sponsors to participate in a Steering Committee to provide direction in the development of the project. In addition to the ICA, government-affiliated organizations from industrialized countries interested in participating were invited to sign a letter of intent committing US$50,000 [39,954 EUR] to the project. Industrializing countries were invited to participate for a US$20,000 [15,982 EUR] commitment.

The first meeting to organize the project was held in February 2000 in Washington DC. In attendance were representatives from ETSU-UK, USDOE, Ministry of Economics of Chile (later represented by the Corporacion Nacional del Cobre de Chile), and the ICA.

\(^1\) Based on analysis conducted by Lawrence Berkeley National Laboratory, Energetics, and the Alliance to Save Energy July 2004
with each sponsor committing US$50,000. As a result of this first organizing meeting, a Steering Committee and a Technical Committee were formed to direct the collaboration. The Steering Committee is comprised of sponsors who oversee the development work and make decisions on the launch, look and feel of the software tool. Sponsors also designate representatives to the Technical Committee, which creates project specifications, oversees the work of the software developer, and reports progress to the Steering Committee. The roles and responsibilities of both Committees and the Project Manager were summarized in writing as the result of this meeting.

The ICA became the project manager responsible for receiving and disbursing funding, entering into contracts, and carrying forward the business of the collaboration. After substantial discussion, the initial sponsors decided not to entertain financial participation by motor equipment manufacturers so that the ensuing software would be viewed as “product-neutral” on a global basis. The first meeting of the Technical Committee was also held in February 2000, during which the work on a specification for the international software was begun. Figure 1 provides an overview of the organizational structure.

Figure 1: Organization Chart - International Motor Software Project

During the course of the software development, the European Union (European Commission-Joint Research Centre or EU-JRC) and Natural Resources Canada (NR Canada) joined the collaboration, with each providing substantial financial as well as in-kind contributions. These additional sponsors expanded the scope of the project in several ways that are described in the next section.
3   Designing IMSSA

The first step in developing what is now known as the International Motor Selection and Savings Analysis (IMSSA) software tool was to develop a specification. An initial set of deliverables was identified prior to the first Steering Committee meeting and then refined as a result of the Steering and Technical Committee meetings. The Technical Committee developed a specification and the collaborative issued a request for proposal to select a contractor to complete the work.

<table>
<thead>
<tr>
<th>Mission</th>
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<tbody>
<tr>
<td>The purpose of the International Motor Software Project is to:</td>
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<tr>
<td>• encourage greater use of energy efficient industrial electric motors; and</td>
</tr>
<tr>
<td>• increase awareness of motor system efficiency worldwide.</td>
</tr>
<tr>
<td>We will do this by creating a software tool that provides industrial users of motor systems with greater access to performance and decision-making information concerning energy efficient motors systems.</td>
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<tr>
<th>Goals</th>
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<tr>
<td>• Create a flexible software shell that can accommodate, with a minimum amount of technical support, motor databases developed for specific motor markets (as initially determined by sponsors)</td>
</tr>
<tr>
<td>• Build on lessons learned and key features from existing motors software developed by the project sponsors and others</td>
</tr>
<tr>
<td>• Prepare a detailed manual in English and Spanish for sponsors and others to use in linking the software shell to specific motor databases</td>
</tr>
<tr>
<td>• Provide technical support required to successfully launch the software in the sponsors’ designated markets</td>
</tr>
<tr>
<td>• Make the software broadly available under guidelines developed by the Steering Committee and build an awareness campaign for the software</td>
</tr>
<tr>
<td>• Seek ways to use the project collaboration to build and strengthen relationships, enhance trade opportunities, and improve communications and information transfer</td>
</tr>
<tr>
<td>• Support the movement towards global harmonization of motor efficiency testing standards and energy efficiency standards.</td>
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</table>

The initial deliverables for the collaboration were identified as 1) a common motor management software shell that interfaces with each sponsor’s database of motors 2) a detailed instruction manual and 3) technical support after launch of the software.

The Technical Committee performed due diligence by examining four existing motor software tools, including EURODEEM (EU), Evaluacion Energetica de Motores Electricos de Induccion (Mexico), EVAMOTOR (Chile), and MotorMaster+ (US). As the result of this work, the Committee determined that MotorMaster+ appeared to be the most comprehensive, while the EVAMOTOR software offered the user the option of either a rapid analysis or a more comprehensive analysis. Both the EURODEEM and Mexican software tools appeared to be based around MotorMaster+ principles.
The Technical Committee decided to develop both the shell and the users manual in English and Spanish, with the Spanish-language work occurring through arrangements with the Chilean Ministry. Later on, French was added.

Anticipated users of the software include:

- project or facility engineers at industrial plants
- operators with limited technical knowledge on motors
- equipment suppliers and distributors
- engineering professionals and energy service companies

Prior to the contractor beginning development of the shell, the sponsors decided to survey selected end users to determine the key features desired in the software. This was accomplished by assembling a focus group and providing a demo of the current version of MotorMaster+, and by describing other possible features.

### 3.1 Key Features of the Software Shell

The committee agreed to pursue both a rapid analysis function (a feature of EVAMOTOR) and a comprehensive capability (a feature of MotorMaster+). An introductory estimating tool to attract interest in further analysis was also considered desirable, but later dropped from the project because of difficulty obtaining the rights to an existing estimator product.

A specification was developed and a Request for Proposal issued. Key capabilities of the software include:

- able to display operating parameters and specifications for both North American (NEMA) and metric (IEC) motors;
- capable of accepting and using data from motor manufacturers' databases containing full and part-load efficiency values taken in accordance with the NEMA IEEE 112 testing protocol or IEC 60034-2;
- capable of containing multiple motor manufacturers' databases for three-phase motor models. Motor performance data may be referenced to the IEEE test protocol, the IEC protocol, or be submitted for both. The database and the software have the capability of containing and displaying motors varying from 1 to 500 hp for the 60 Hz models and from 0.75 to 370 kW for 50 Hz service;
- multi-language capability (with the initial version developed in Spanish and English) and ability to display and conduct economic analyses using local currencies;
- allows users to insert applicable import tariffs, efficiency standards, and motor efficiency and list price default values, and
- permits user entry of country-specific motor repair and replacement cost defaults and estimates of motor rewind-related efficiency losses.
Key features include:

- Splash Screen which provides users with the ability to select their preferred language, motor operating frequency, motor efficiency test standard and currency;

- Motor Selector which allows a user to conduct energy-efficient motor savings analyses without ever accessing the main body of the software package; and

- Detailed Motor Analysis, which allows the user to compare the annual running cost of an existing standard efficiency motor model with that of an energy-efficient model. The module allows the user to determine cost-effectiveness for "New Purchase," "Repair-versus-Replace," and "Replace Existing Motor" scenarios.

Other features include user-entered Electricity Rate Schedules, Financial Analysis, and Motor Rebate Program modules.

After considering several contractors, the Technical Committee recommended and the Steering Committee accepted the proposal from Washington State University (WSU). Due to funding limitations, the collaboration elected not to include the inventory and maintenance function in the initial software shell development.

The rights to the software are held jointly by ICA and WSU, with the understanding that the project sponsors (Steering Committee) will be consulted and approve any changes to the software beyond the original scope of work.

3.2 Providing an Environment for Standardization

IMSSA is designed to provide a platform that helps facilitate harmonization of motor standards through the collection of motor performance data in a common format. IMSSA provides motor manufacturers, most of whom serve global markets, with a defined set of data fields that can be used to describe the features and efficiency of most motor types regardless of the country of origin or destination. It also provides policymakers with ready access to motor performance for the purpose of determining requirements for energy efficiency labels. Because it provides the opportunity to access a large body of motor data reported in a common format and available from a single source, this standardized database format aids harmonization efforts. Although the software splash screen currently asks the user to select either IEEE- or IEC-tested motors and then calls up the appropriate database, if test standards become harmonized at some time in the future, these databases could readily be integrated.

3.3 Preparing for Launch

The initial development of the IMSSA shell was completed in mid-2003. The shell was initially populated with a database of 25,000 North American IEEE-tested motors. However, during the development of the software shell, the European Union-JRC became increasingly involved in the collaboration and contributed their database of 7,200 IEC-tested motors for inclusion in IMSSA. Inclusion of these data and the ongoing
commitment of the EU to work with European manufacturers to update these data was a significant contribution. In July 2003, Natural Resources Canada approached the collaboration with a request to join and an offer to fund some additional features such as:

- capability to enter demand charges based upon monthly peak kVA rather than kW readings;
- ability to convert energy savings (kWh/year) into greenhouse gas emission reductions (in pounds or kg per year). Display emission reduction benefits on all appropriate on-screen displays and printed reports;
- addition of a French language module and supporting French-language software manual, and
- addition of Canadian currency and utility rate structures as selection options.

The enhanced software, including North American and European motor databases, was released to the sponsors for beta-testing in September 2003. Following the beta-test period, additional modifications were made to IMSSA and the final product was released to the sponsors for in-country launch in March 2004.

4 The IMSSA Experience

In keeping with the organizational plan for IMSSA, each sponsor is responsible for developing a program to release the software to their own constituencies. To date, three sponsors have released the software: Natural Resources Canada, U.S. Department of Energy, and Corporacion Nacional del Cobre de Chile. In June 2004, the U.S and Canada organized a joint announcement at a conference of the Electrical Apparatus and Service Association (EASA), the largest trade association for motor distributors and rewind services in North America.

4.1 The U.S Experience

In 1993, the USDOE first launched a motor management tool, MotorMaster+, in cooperation with Washington State University. Since that time, USDOE, through its Industrial Technologies Program (ITP) has continued to refine and add features to MotorMaster+. Although MotorMaster+ is very popular, comprehensive, and includes many of the same features that are in IMSSA, USDOE elected to participate in the IMSSA collaboration as a way of pooling resources and knowledge to develop a truly international software tool. Additional features include: a 32-byte platform, a quickly accessed Motor Selector module, multi-language capability, and the ability to conduct repair/replacement analysis on a broader range of motors, which is particularly impor-

2 During the development of IMSSA, the UK sponsorship transitioned from ETSU to the UK Action Energy (Carbon Trust), which has not developed any plans for the software release. EU plans are pending.
tant to US companies with overseas operations who are interested in improving motor system efficiency.

After announcing the availability of MotorMaster+ International at the June 2004 Electrical Apparatus and Service Association meeting with colleagues from Canada, the USDOE made the software available online from the USDOE website as MotorMaster+ International at http://www.oit.doe.gov/bestpractices/software_tools.shtml USDOE also included a feature in the electronic newsletter, ITP E-Bulletin, which goes out to more than 10,000 industrial readers. To date, approximately 1400 copies of MotorMaster+ International have been downloaded. The distribution figures are expected to increase substantially when the tool is included on the ‘Decision Tools for Industry’ CD. MM+ International is also being incorporated into the ITP Motor Systems training curricula. Interactive web-based demonstrations of the tool are planned in 2006.

To accommodate existing users of MotorMaster+, USDOE continues to make both software products available until such time as the Inventory Management, Batch Analysis, Energy Accounting - Savings Validation / Tracker, and Maintenance Logging features (currently included in MotorMaster+) are incorporated into MotorMaster+ International. Discussions concerning an IMSSA 2.0 that would include these features are already underway.

4.2 The Canadian Experience

IMSSA is sponsored by National Resources Canada under the Office of Energy Efficiency’s EnerGuide for Industry initiative, which provides information and tools to help energy-wise companies make better educated, more energy-efficient selections when purchasing "off-the-shelf" equipment for their specific applications. For the Canadian market, IMSSA is branded CanMOST (Canadian Motor Selection Tool) and OSMCan (Outil canadien de sélection des moteurs au Canada) in French. Canadian require-
ments added to IMSSA include: a French language version, the ability to handle Canadian utility rate structures and rebate schemes, prices in Canadian dollars, the calculation of greenhouse gas emissions, and the addition of some 575 volt motors available only in Canada.

Officially launched in June 2004, CanMOS T was made available for download from EnerGuide for Industry’s Website (http://egi.gc.ca) in November of that year. A number of approaches have been taken to reach the target audience of industry decision makers and buyers:

At launch time public relations were used to reach a large audience, increase awareness of the initiative, and encourage trial. A press release was issued, and an article was placed in trade press.

In the spring of 2005, a direct mail piece was inserted into the highest circulation English and French industry publications (total reach 50,000). In the same timeframe 3,000 CanMOS T CDs were mailed to purchasers of an Electric Motor Handbook (The Electricity Forum, 2004).

Participation at specific large industry trade shows (namely manufacturing and pulp and paper) with strategic partners such as utilities, have allowed for brief but personal interaction with key target audience segments, such as plant design and maintenance people, or a specific industry sector.

CanMOS T is constantly being presented at various forums (industry sector task forces, energy efficiency conferences, industrial information sessions, motor workshops…). These are a good opportunity for in-depth presentations to smaller but highly receptive groups.

As of March 2005, in addition to the 3,000 CD’s mailed, there were 427 unique downloads of CanMOS T from the Website, 369 of these originating from Canada.
Public opinion research is currently under way (May 2005) to gauge users’ level of satisfaction with the software and identify any barriers to use, as well as assess the need for a second generation of CanMOST that would add motor inventory management, batch analysis, energy accounting and maintenance logging capabilities.

Next for CanMOST promotion is to step up the collaborative work already under way with electrical utilities, to increase the demand for premium efficiency motors and offer CanMOST as a unique tool to help identify those best suited to specific applications. Namely, CanMOST will be used by Hydro-Québec, one of Canada’s largest electric utilities, as a selection tool for a premium motor incentive program. One-day workshops the overall benefits of premium efficiency motors are also being developed to increase awareness and uptake by industry.

### 4.3 The Chilean Experience

In Chile, on 25 November 2004, CODELCO and the Comisión Nacional de Energía (CNE) launched their customized version of IMSSA. A workshop was held which was well-attended. Work has also started on dissemination within Spanish speaking Latin America.

### 5 Next Steps

As the launch of IMSSA proceeded, the Steering Committee continued to meet and discuss issues concerning the long-term support of the software. During development, the original vision of the software- that of a common shell with country-specific databases maintained by the host countries- was modified slightly. The new vision of IMSSA is that of a common software shell that comes loaded with North American, European, and any other national or regional motor databases submitted by sponsors.
Users can select which databases to access when using the software. The North American and European databases are maintained with the software through ongoing in-kind support of USDOE and the EU.

The Steering Committee arranged for ongoing limited technical support from WSU in order to support sponsors who are trying to deal with non-routine technical problems. In addition, WSU will also provide software support as required to maintain the functionality of the software.

The Steering Committee has also decided to invite government agencies or non-governmental organizations (NGOs) that would like greater involvement to become sponsors at a lower cash investment than the founding sponsors. New sponsors would include organizations that agree to invest in the expansion of the capabilities of the existing software by adding a language and/or a motor database customized for use by a country. Sponsors will also have the opportunity to influence the future direction of IMSSA through participation in the collaborative decision making process and are recognized on the splash screen. A description of the benefits of sponsorship is available.

Finally, the Technical Committee has developed a specification for additional features, including Inventory Management, Batch Analysis, Energy Accounting - Savings Validation / Tracker, and Maintenance Logging. The Steering Committee will be reviewing the cost and merits of these additional features over the next few months and deciding on additional development.

With the participation of additional countries, especially in Asia and the Indian subcontinent, IMSSA has the potential of becoming a truly global motor selection and savings analysis tool. By doing so, the IMSSA collaborative will be well on its way to achieving its goals of 1) encouraging greater use of energy efficient industrial electric motors, 2) increasing awareness of motor system efficiency worldwide, and 3) creating an environment in which harmonization of motor standards is encouraged.

6 References


Using Software Tools to Improve Motor Efficiency at a Shipyard

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Abstract

The U.S. Department of Energy’s MotorMaster+4.0 software tool was used at a U.S. Navy shipyard to identify old standard efficiency motors that are candidates for replacement with NEMA Premium™ efficiency motors. The software was used to determine which operating motors should be immediately replaced with Premium efficiency motors, which motors should be replaced at their time of failure, and which motors should be repaired (rewound) and returned to service. The immediate replacement of 65 standard efficiency motors will produce an expected annual energy savings of 307,493 kWh, with a reduction in facility electrical demand of 37.1 kW. Annual savings are valued at $11,685 USD at an electrical energy rate of $0.038/kWh. It is also cost-effective to replace an additional 259 standard efficiency motors with Premium motors at their time of failure. The eventual replacement of these 259 motors will provide an additional 376,123 kWh of annual energy savings valued at $14,290 per year.

1 Overview/Summary

The U.S. Department of Energy’s MotorMaster+4.0 software tool was used at a U.S. Navy shipyard to identify old standard efficiency motors that are candidates for replacement with NEMA Premium™ (Premium) efficiency motors. The software was used to determine which operating motors should be immediately replaced with Premium efficiency motors, which motors should be replaced at their time of failure, and which motors should be repaired (rewound) and returned to service. The software considered purchase prices and installation costs of replacement motors, and determined expected annual energy savings, simple paybacks, reductions in electrical demand, and decreases in facility operating costs.

During the motor survey phase, 824 in-service motors rated 3 horsepower (2.2 kW) and above were identified. Nameplate data was gathered, special and definite purpose motors were clearly identified, and the motor location and type of equipment driven by each motor was noted. For 324 of these motors, operating schedules were determined and field measurements taken (voltage, amperage, power factor, speed, or kilowatts). MotorMaster+ Inventory and Batch Analysis features were then used to determine the motor load, efficiency at the load point, annual electrical energy use, and energy savings due to replacing existing motors with Premium efficiency motors.

The immediate replacement of 65 standard efficiency motors will produce an expected annual energy savings of 307,493 kWh, with a reduction in facility electrical demand of 37.1 kW. Annual savings are valued at $11,685 USD at an electrical energy rate of $0.038/kWh. The Navy’s total cost for purchase and installation of the 65 Premium efficiency motors is approximately $114,594 after a Bonneville Power Administration efficiency incentive of $36,899 is taken into account. The simple payback to the Navy for the immediate motor replacement project, based only on energy savings, is 9.8...
years. This payback is within the 10-year cost-effectiveness criteria used by the shipyard.

It will also be cost-effective to replace an additional 259 standard efficiency motors with Premium models at their time of failure. The eventual replacement of these 259 motors will provide an additional 376,123 kWh of annual energy savings valued at $14,290 per year at current rates.

The remaining 150 standard efficiency motors cannot or should not be replaced with Premium efficiency models. These motors should be repaired and returned to service when they fail. This population includes special and definite-purpose motors—such as vertical shaft and close-coupled pump motors—which carry a price premium and/or are not available in models that meet the minimum full-load efficiency standards for NEMA Premium™ motors. Large motors with low run times, such as fire pumps, oil transfer pumps, and drydock dewatering pumps are also poor candidates for upgrading to Premium efficiency motors.

Challenges included estimating the average load for motors not operating at the time of the survey and accounting for load increases when centrifugal equipment is driven by higher speed Premium efficiency motors. Unfortunately, motor age and rewind history were not available and so could not be factored into the energy savings analysis. Generally, motor losses increase when motors fail and are repaired. The incorporation of an appropriate "handling" adder into the motor installation costs was the most difficult part of the study. This handling cost is applied to motors with restricted access. Restricted access means that additional equipment or tools—such as chain falls, man lifts, or cranes—are necessary to access the motor or install the motor onto equipment.

Potential energy savings at the site were less than expected, as 305 existing motors were already Energy Efficient or Premium efficiency models. The U.S. Department of Energy's Bonneville Power Administration (BPA) funded the motor survey and efficiency improvement plan through the BPA Conservation Augmentation program.

2 The MotorMaster+ Software Tool

MotorMaster+4.0 was developed for the U.S. Department of Energy by the Washington State University Extension Energy Program to support motor management functions at medium-sized and large industrial facilities. The software is designed for utility auditors, industrial energy coordinators, plant or consulting engineers, industrial service providers, and plant maintenance staff.

MotorMaster+ allows for motor and motor systems improvement planning through identifying the most efficient action for a given motor repair or purchase decision. MotorMaster+ can be used to identify inefficient or oversized in-plant motors and compute the energy and demand savings associated with selection of a Premium efficiency replacement model.
MotorMaster+ contains an in-plant motor Inventory module, maintenance logging and tracking features, a manufacturers' motor price and performance database, and energy conservation analysis, life cycle costing, and motor load and efficiency estimation capabilities. The software also has energy accounting and savings verification functions.

The Inventory module contains motor nameplate information, identification, process, and location codes; load type, operating hours, and working-environment descriptions; and measured data such as voltage, amperage, power factor, and speed at the load point.

One can conduct descriptor-based motor inventory sorts within the Inventory module, scan for motors operating under abnormal power supply conditions, and determine existing motor loads and efficiencies after entering field measurements. A Batch analysis can be conducted to determine the cost-effectiveness of replacing all motors in a given facility with Premium efficiency motors. Energy and cost savings are aggregated for all replacement motors having a simple payback below a selected value.

MotorMaster+ Version 4.0 also includes

- A database of performance and price information on more than 25,000 National Electric Manufacturers Association (NEMA) Design A, B, C, and D three-phase motors. The motors range from 1 to 2,000 horsepower (hp), with speeds of 900, 1,200, 1,800, and 3,600 rpm, and a wide range of enclosure types and service voltages. Full- and part-load efficiency values are measured in accordance with the IEEE 112 protocol to guarantee consistency. Manufacturers supply the information electronically, and the database is periodically updated.
- Technical data that can help optimize a drive system, such as data on motor part-load efficiency and power factor; full-load speed; locked-rotor, breakdown, and full-load torque; and no-load and locked-rotor amperage.
- Purchase information, including list price, warranty period, model name, catalog number, motor weight, and manufacturer's contact information.
- Analysis features that calculate the energy savings, dollar savings, simple payback, cash flows, and after-tax rate of return on investment from using a particular Premium efficiency motor in a new purchase or retrofit application. Variables such as motor efficiency, purchase price, energy costs, operating hours, load factor, and utility rate schedule and motor rebate program data (including minimum qualifying efficiency and rebate dollar values) are taken into account.
- Energy accounting, conservation savings tracking, and greenhouse gas emissions reduction reporting capabilities.
- Menus and extensive help screens that make MotorMaster+ easy to learn and use.

The following U.S. Department of Energy website contains additional information and the option to download the MotorMaster+ software tool:

http://www.oit.doe.gov/bestpractices/software_tools.shtml
3 The Motor Survey

One goal of the shipyard study was to survey all in-service three-phase motors that are rated at 3 hp (2.2 kW) or above. The survey consisted of three parts: gathering motor nameplate data, determining each motor's operating schedule, and collecting field measurements.

A "Motor Nameplate and Field Test Data Form" was filled out and input to the software for each of 824 in-service motors. Each motor is assigned to a Building Number so that operating motors can readily be sorted and displayed by Building. Data collected includes the motor Location, Manufacturer, Model Name, Serial Number, Horsepower Rating, Synchronous Speed, Enclosure Type, NEMA Design Type, Design Voltage and Wired-For Voltage, Frame Designation, and Performance Values such as Full-load Amps, Power Factor, and Full-load Efficiency (when stamped on the nameplate). We also collected the Service Factor, Temperature Rise, Insulation Class, and kVA Code.

The motor age and rewind history could not be ascertained due to lack of records. Generally, motor losses increase by 0.5% to 1.0% when motors fail and are repaired, so neglecting rewind losses will tend to understate the expected energy savings. C-Face, Vertical Shaft, U-Frame and Close-Coupled Pump drive motors were clearly identified. We also identified the type of load or equipment that each motor is coupled to. The 824 motors contained within the shipyard survey represent 23,956 connected motor horsepower.

Field measurements were taken for 324 operating motors. A Hioki power meter or Fluke 43B multi-meter was used to collect either instantaneous kW readings, or Voltage and Amperage data for each motor. A strobe tachometer was used to measure driven equipment speeds for belt-driven fan loads. Annual operating hour information was supplied by the Navy. Operating hour and field measurement data were input to the MotorMaster+ software's Inventory module. The software uses utility data, annual operating hours, and one of three internal load and efficiency estimation techniques to determine the loading on each motor, efficiency at the operating load point, and annual operating costs.

4 Motor Efficiency and Average Motor Load Reports

The National Electrical Manufacturer's Association (NEMA) has established minimum nominal full-load efficiency standards for motors that may be designated as “NEMA Premium”™ or as “Energy Efficient” motors. The NEMA Premium standards apply to 1 hp (0.75 kW) to 500 hp (375 kW) motors rated at 600 volts and below and to 200 hp (150 kW) through 500 hp motors rated from 600 to 6600 volts that operate at 1200, 1800, or 3600 RPM.

Of the existing in-service motors at the shipyard, 794 fall under the NEMA standards—83 qualify as NEMA Premium motors, 221 are Energy Efficient, while 490 are of standard-efficiency design. Larger motors are more likely to already be Energy Efficient or Premium models; thus, while only 38.3% of the BNC motors by number are Premium...
or Energy Efficient motors, 50.2% of the total connected horsepower already meets or exceeds one of the NEMA efficiency standards. The Navy has obviously been specifying and purchasing high efficiency motors for some time.

The MotorMaster+ internal load and efficiency estimation algorithms show that the average shipyard motor was loaded at 67.6% of its nameplate rated output. When determining energy savings due to replacing in-service standard efficiency motors, this value was used as a default for all motors lacking field measurements.

5 Motor Energy Savings Methodology

The MotorMaster+ Batch module allows users to determine energy savings due to the replacement of “batches” or selected populations of motors with higher efficiency motors. A replacement motor must have the same horsepower, speed, enclosure type, voltage rating and special or definite purposes as the existing motor. The load that is imposed upon the existing motor by the driven equipment is assumed to be identical with that placed upon the replacement higher efficiency motor. All in-service fan and pump drive motors are assumed to have a constant load. Motors with known variable loads are dropped out of the Batch Analysis.

Energy savings for each motor are calculated as:

\[
\text{kWh} = \text{hp} \times \left(\frac{\text{Load}}{100}\right) \times 0.746 \times \left(\frac{100/\eta_{\text{std}} - 100/\eta_{\text{PE}}}{\eta_{\text{PE}} - \eta_{\text{std}}}\right) \times \text{Operating Hours}
\]

Where:

- \(\text{kWh}\) = Annual energy savings in kilowatt-hours
- \(\text{hp}\) = Motor rated hp
- \(\text{Load}\) = Motor load factor in %
- \(\eta_{\text{std}}\) = Efficiency of the Existing Standard Efficiency Motor at Load Point, %
- \(\eta_{\text{PE}}\) = Efficiency of the New NEMA Premium™ Motor at the Same Load, %
- \(\text{Operating Hours}\) = Annual motor operating hours

The value of the energy savings obtained by replacement of standard efficiency motors is calculated by multiplying the annual kWh savings by $0.038/kWh. This fixed energy charge contains both energy and demand cost components and is used by the Navy to evaluate all conservation investments. Simple payback (in years) is equal to the sum of the motor purchase and installation charges, less the BPA incentive, divided by the value of the annual energy savings.

In starting the MotorMaster+ Batch run to calculate energy savings, the software was directed to use the actual motor load (determined from field measurements) when it is available, and a default motor load of 67.6% for all other standard efficiency motors. Only in-service standard efficiency motors were analyzed, as it is not cost-effective to upgrade existing Energy Efficient motors with Premium efficiency models.
The Batch analysis aggregates the energy and dollar savings from the sub-population of in-service standard efficiency motors that exhibit simple paybacks that meet the Navy’s cost-effectiveness criteria. No individual motor rated at 25 hp and below could have a simple payback that exceeds 10 years. The cost-effectiveness cut point is raised to 15 years for motors 30 hp and above, because these motors are likely to remain in service for more years. The BPA conservation incentive of $0.12/kWh is taken into account when determining simple paybacks.

For motors supplied by a 208-Volt service, the software calls for replacement with 200-Volt rated motors. Older U-Frame motors are to be replaced by T-Frame motors with transition bases. To minimize the spare inventory, all motors wired for 220, 230, 440, or 460 Volt service are to be replaced by dual voltage 230/460 Volt motors. (Note: above 100 hp, replacement motors are typically rated as 460 Volt motors and the dual voltage rating is not required). Definite purpose motors designed to drive close-coupled pumps (with JP and JM frame designations) are to be replaced by motors meeting the NEMA Energy Efficient motor standards, as Premium efficiency replacements are not available. Because definite purpose close-coupled pump motors are not covered by the federal EPAct mandatory minimum full-load motor efficiency standards, efficiency improvements lag behind those available for general purpose motors.

A centrifugal load/speed correction factor is applied to all standard efficiency motors that drive centrifugal fans and pumps. This is done automatically within MotorMaster+ to account for the slight increase in the load imposed on the Premium motors by the driven equipment due to the motor’s higher operating speed. Premium efficiency motors generally tend to rotate fans and pumps at a slightly higher speed—on the order of 15 to 30 RPM for an 1800 RPM synchronous motor. For centrifugal equipment, flow varies linearly with speed. When driven by a Premium efficiency motor, a fan will supply a small amount of additional airflow and consume an additional increment of energy to do so. Within MotorMaster+, this increase in energy use is automatically subtracted from the savings produced due to installation of the Premium efficiency replacement motor.

While pulleys and sprockets are available with a wide range of pitch diameters that would allow for correcting the speed increase due to installation of Premium efficiency motors, the process used to select the appropriate sprocket combination and belt length must be completed by a power transmission specialist. Note that a drive end sprocket and bushing, a belt, and a driven-equipment sprocket and bushing must be specified for each motor, with the components selected to maintain the existing speed ratio. The additional energy savings obtained from speed correction will not offset the costs required to perform the necessary analysis and to purchase and install the new power transmission components. Savings estimates given in the shipyard report do not include additional benefits due to speed correction.
6 Motor Equipment Cost Estimates

The costs for the Premium efficiency replacement motors are the manufacturer’s list prices for Energy Efficient and Premium efficiency Baldor motor models contained within the MotorMaster+ manufacturer’s database adjusted by a 20% list price discount factor. The 20% discount factor is derived from several components including an expected 50% manufacturer’s list price discount, with a 10% price increase for 2005 motor models, and a distributor profit equal to 10% of the full-list price (or 20% of the discounted list price). An additional 10% price adder was applied to account for the relatively remote location of the shipyard relative to motor distributor’s warehouses.

7 Motor Installation Cost Estimates

Motor installation costs are taken from the 2005 release of RS Means Facility Construction Cost Data. Bare labor rates and estimates of labor hours for installation of motors of various horsepower ratings are based on union wages averaged for 30 major U.S. cities. Total overhead and profit for electricians is taken as 53.8% of the bare labor rate. This cost multiplier includes an overhead of 16%, profit of 15%, Workers Compensation Insurance at 6.5%, Federal and State Unemployment costs at 6.2%, Social Security Taxes (FICA) set at 7.65%, and miscellaneous costs totaling 2.44%

A “handling” adder—also taken from Means—is applied to motors with restricted access. General access means access to the motor, based both on location within the facility and location of the motor in or on the driven equipment. Normal access does not require special tools or equipment to get to the motor. Restricted access means additional equipment or tools, such as chain falls, man lifts, or cranes, are necessary to access the motor or install the motor onto the equipment. It is assumed that 50% of the motors at the shipyard offer some form of restricted access. A 15% adder was also applied to the base and handling labor rates, overhead, and profit to account for motor testing and lost productivity due to the facility’s security requirements. Total motor installation costs are summarized in Table 1.

Belts are generally not replaced at the time of motor replacement. It will be important to note the condition of the belts and the pulley at the time of replacement and make recommendations for future actions. If a pulley has excessive wear, the belt can ride low in the groove and result in greater friction losses and an increased load being imposed upon the motor. Motor couplings are generally held in place with a set screw and also are reusable. Pump mechanical seals and packings do not require replacement during a motor efficiency improvement project—unless the pump seal was previously leaking and that leakage caused the premature failure of the motor. It is recognized, however, that some unanticipated costs will occur due to the need to replace damaged or worn components, the requirements for frame adapters (for downsized motors or U-frame to T-frame conversions), and for replacement of starter fuses when downsizing motors. A cost adder of $100 per motor is included in our analysis to account for such charges.
The disposal of replaced motors does not impose additional motor replacement project costs. In fact it should be a positive for the contractor, as scrap prices are about $0.12 per pound. There should not be any hazardous materials concerns associated with the disposal of three-phase motors.

It is often most cost-effective to replace older standard efficiency motors when they fail, as the simple payback is based upon an incremental cost (new motor cost less repair costs) instead of the full cost of purchasing and installing a new Premium Efficiency motor. Motors may also incur a small decrease in efficiency—on the order of 0.25% to 1.0%—when they are rewound. The energy savings project also does not have to offset installation costs, as the failed motor has to be removed in any case and reinstalled.

Table 1: Motor Installation Cost Estimates

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<th>Motor hp Rating</th>
<th>Base Installation Cost, $USD</th>
<th>Handling Cost, $USD</th>
<th>Subtotal $USD</th>
<th>Overhead @ 53.8%</th>
<th>Sub-total, $USD</th>
<th>Security and Testing @ 15%</th>
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8  Motor Sizing and Operational Issues

8.1  Oversized and Overloaded Motors

Motors that operate at less than 40% of full-load are considered for replacement with a downsized Premium efficiency motor. A downsizing routine built into the MotorMaster+ software examines the cost-effectiveness of all equivalent motors and downsized replacement alternatives, and then selects the one with the most rapid simple payback. Due to uncertainties in load estimation, the loading on the replacement motor is not allowed to exceed 85%. Downsizing makes sense as the equipment and installation costs are much less when smaller replacement motors are selected.

Twenty-one motors at the shipyard are oversized. Many are air handling or exhaust fan drive motors with constant loads in the range of 23% to 39%. These motors should be replaced with downsized motors that are matched to their load requirements. Downsizing is not recommended for motors driving known variable loads such as augers or mixers. When motor downsizing does take place, overload protector (heater) fuses must be replaced in the motor starter. The circuit breaker is selected to protect the wiring up to the motor and the starter. Since the conductors aren’t downsized, the circuit breaker does not need to be changed. Electronic starters are often adjustable. Conductor sizing is not an issue when motors are downsized, but should be examined whenever an overloaded motor is replaced with a larger unit.

Field measurements were retaken at two motors to verify that they are overloaded. An overloaded motor is one whose load exceeds its Service Factor, typically defined as 115% of full-rated load. For instance, a 60 hp Supply Fan motor was found to be loaded to 122% of its nameplate rating and when it fails should be replaced with a 75-hp Premium efficiency motor.

8.2  Operation under Conditions of Voltage Unbalance

Voltage unbalance is defined by the National Electrical Manufacturers Association (NEMA) as 100 times the absolute value of the maximum deviation of the line voltage from the average voltage on a three-phase system, divided by the average voltage. For example, if the measured line voltages are 462, 463, and 455 volts, the average is 460 volts. The voltage unbalance is:

$$100 \times \left(460 - 455\right) / 460 = 1.1\%$$

Voltage unbalance is probably the leading power quality problem that results in motor overheating and premature motor failure, as voltage unbalance at the motor stator terminals causes phase current unbalance far out of proportion to the voltage unbalance. Unbalanced currents lead to torque pulsations, increased vibrations and mechanical stresses, increased losses, and motor overheating which results in a shorter winding insulation life. Eleven motors at the shipyard are operating under conditions where the voltage unbalance is in the range of 1.6% to 2.0%. It is recommended that voltage
unbalance at the motor terminals not exceed 1%. When unbalanced voltages are detected, a thorough investigation should be undertaken to determine and eliminate the cause.

9 Results and Conclusions

MotorMaster+ proved to be a very effective motor management tool. In particular, the in-plant Inventory and Batch analysis modules serve as a repository for motor nameplate data and field measurements and enable users to quickly create a comprehensive motor efficiency improvement plan.

The shipyard study concludes that it is cost-effective to immediately replace 65 operating standard efficiency motors. These motors have a combined 1,113 horsepower, representing approximately 4.6% of the facility’s total motor-connected horsepower. Replacing the 65 motors with motors meeting NEMA Premium standards provides an expected annual energy savings of 307,493 kWh and a demand reduction of 37.1 kW. These savings are valued at $11,685 annually. The total equipment and installation cost for the motor replacement project is estimated at $114,594 after taking an expected $36,899 BPA incentive payment (@ $0.12 per kWh of savings) into account. The simple payback for this project is 9.8 years.

The shipyard can continue to improve the overall energy efficiency of their motor-driven systems by:

- Specifying Premium efficiency motors for all new general purpose motor purchases (where the motor is expected to operate over 2,000 hours annually).
- Specifying that rotating machinery supplied by original equipment manufacturers be equipped with Premium efficiency motors.
- Specifying Energy Efficient motors for new close-coupled pump and vertical shaft motor applications.
- Rewinding and returning to service all failed Energy Efficient and Premium efficiency motors. Ensure that high quality repairs are obtained by rewinding to the Department of Energy’s “Model Repair Specifications for Low Voltage Induction Motors.”
- Using the Department of Energy MotorMaster+ software tool for motor inventory management and to track the maintenance and repair histories of shipyard motors.
- Tagging 259 additional standard efficiency motors so they are replaced with Premium efficiency motors when they fail.

Creating a motor database and developing a motor efficiency improvement plan represent two of many steps being taken at the shipyard to reduce energy costs. The shipyard has adopted motor efficiency upgrade specifications that call for all new motors to be “inverter-ready” or compatible for use with pulse-width modulated adjustable speed drives. This requirement is in place to facilitate the future conversion of building HVAC systems from constant to variable volume operation.
Motor System Audit and Software Tools II
ProMot: A Decision Support Tool for the Promotion of Energy Efficient Motor Systems

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Abstract

A decision support tool is being developed, within the framework of a project co-financed by SAVE, aiming to aid end users to explore the possibility of energy savings, in motor systems of an industrial or tertiary installation. It has been designed for users having basic technical expertise. Motor systems considered and analysed by the tool include electric motors, pumps, compressed air as well as chillers (heat pumps), while fans and other relevant topics are also addressed. General introductory information is provided on the topics treated. The tool helps in auditing an installation, and performing simple meaningful calculations of purchasing, replacing existing or retrofitting electric motor systems. These technical and economic calculations are based on equipment data retrieved from widely accepted and regularly updated European databases and methodologies.

In this paper, the characteristics of the tool are briefly described. Emphasis is given on the structure, methodology and operational aspects of chillers module.

1 Presentation of the tool

Motor systems in industry and service sector buildings are the largest single type of use of electricity. Electric energy savings potential is huge and has been estimated by European Commission programmes to exceed 100 TWh in each of the two sectors across Europe.

ProMot decision support tool has been designed to help users having basic technical expertise to explore the possibility of energy savings in motor systems of an industrial or tertiary installation. It analyses four basic types of electricity driven systems:

1. Motors and Drives
2. Compressed Air Systems (CAS)
3. Water Pumps
4. Chiller (heat pump) systems.

Motor and Drive Systems module informs the user about the existing motors efficiency classifications and the benefits of using a high efficient motor and drive system. It also guides the user on proper sizing of a motor system and gives tips on how he can reduce transmission losses. The calculation part of the module is based on the EuroDEEM database, which currently contains data of over 18,000 motors (provided by manufacturers). The user can calculate the energy and operating cost savings potential of replacing, repairing or buying a new motor (Washington State University 2004).
CAS Systems module takes the user through a “Guided Tour” of the existing system, to identify the priority actions for energy savings. It provides information, cost and saving analyses for three cases:

1. Low cost measures to improve operation and maintenance.
2. Major repair or extension.
3. Design, purchase and install a new compressed air system.

The Pumping and VSD Systems module examines the possibilities for energy savings through (clean water) pumping equipment or control system. Like other systems, the initial purchase cost of a pump is a small fraction of its operating energy cost. The introductory part of the module provides general guidance on choice of pumps and associated systems. The calculation part lets the user define the nameplate values of pumps and the load profile and calculates the energy consumption based on input data. The benefit of control by VSD (Variable Speed Drives) systems for the given load profile is also treated in this module (Tanner 2005).

Chiller module provides general information on the basic components of a cooling system (chillers, pumps/fans, pipes/ducts, AHUs and FCUs, Ventilation, etc). It provides direct links to the Eurovent-Cecomaf site for up to date information on such products. The calculation part of the Chiller module treats Air and Water Cooled Chillers. In a fashion very similar to the Motors module, the user can calculate the energy consumption and analyze the effect of choosing various chillers for a new or under refurbishment installation. Calculations are based on the Eurovent-Cecomaf database, which currently contains data of about 3600 chillers and is regularly checked and updated.

Figure 1: Layout of the tool

The tool also contains relevant information, such as introductory parts to each module, and results of relevant studies financed by SAVE and other EC programmes. It can
currently be found at www.motorchallenge.ch:8181/promot and it will be transferred to DG JRC upon completion of work.

Analysis to follow will focus on the chiller module.

2 Cooling-Heating Systems

A typical cooling or HVAC system comprises of

- Heating or cooling producing equipment (boilers, heat pumps etc)
- Pumps and/or fans
- Piping networks
- Heat exchangers transferring or absorbing heat from a space or a process.

Current analysis will focus on chillers, as a part of a cooling or an HVAC system. Chillers are defined to be heat pumps (HP) used for cooling, possibly reversible able to produce heat. Studies have shown that about 90% of the primary energy for cooling is consumed by the chiller/HP and the rest 10% by peripheral machinery.

Energy consumption for cooling is of utmost importance during the last years, since it is contributing greatly to the electricity peaks in summer, which destabilise the electricity networks of countries – especially in warm climates, such as, around the Mediterranean region. A number of studies estimate that air conditioning contributes to peaks in excess of 40% (Sofronis 2002)

2.1 Chiller and Energy Efficiency

The chiller is a complicated part of machinery, consisting of a compressor, expansion valve and heat exchanger/s. The refrigerant circulating through, is heated or cooled at various stages to produce the required result. Energy efficiency of a heat pump depends on a number of design choices and parameters such as type of compressor, type of refrigerant, type and control of expansion valve, sizing of heat exchanger/s, etc.

Efficiency, by definition, is the ratio of the energy output of a piece of equipment to its energy input, in like units to produce a dimensionless ratio. The relative efficiency of HVAC equipment is usually expressed as a coefficient of performance (COP), which is defined as the ratio of the heat energy extracted to the mechanical (and/or electrical) energy input. For heat pumps it has become customary to use energy efficiency ratio (EER), during the cooling period and as coefficient of performance (COP) during the heating period.

The overall efficiency of an HVAC system depends on all the parts that comprise the system. For example under sizing of piping networks leads to high energy consumption from the pumps or fans. Pumps, fans and air handling devices are themselves electricity consuming devices. The current document will focus on the “heart” –the highest energy consumer– of the system, namely, the vapour compression heat pump (chiller).
3 Chillers Module Architecture

The chillers module has been setup according to the structure presented in Figure 2. It has been implemented following a three-step schema that involves (a) the chillers database, (b) mathematical models for energy and water consumption estimation, and (c) the presentation layer.

![Diagram of Chillers Module Architecture]

**Figure 2:** Architecture of the chillers module

Chillers module has been developed and operated as a web based application based on the Microsoft.NET platform (ASP.NET technology). The reason for this choice relies on the fact that web-based applications deliver an enormous range of business advantages over traditional standalone desktop applications.

- Internet powered applications provide companies with significant cost and time savings.
- Deployment is simple and less complicated as clients’ possess their own browser software.
- Support and maintenance is also made easier. Businesses avoid the common maintenance problems associated with local applications. Software updates for example can be instant because the application exists only on the web server. Therefore all users access the same version.
For end-users the advantages are just as clear:

- Web based applications are more intuitive and convenient to work with. It is easier to customise the user-interfaces, making them more visually appealing and easy to use.
- Unlike traditional applications, web systems are accessible anytime, anywhere using a PC with an Internet connection.

### 3.1 Eurovent database

Analytical evaluation of a chiller performance is a cumbersome task, leading to questionable results. A decision has been taken in the current project to adopt the Eurovent database for the chillers module. This database contains a great number of parameters, including COP and EER for a significant number of products. Data and products are constantly updated tested and improved. The organisation and the database are recognised by many major HVAC component manufacturers. Equipment covered by the database is presented in Table 1.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
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<th></th>
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<td>Packaged</td>
<td>P</td>
<td>Cooling only</td>
<td>C</td>
<td>Ducted</td>
<td>D</td>
<td>Centrifugal</td>
<td>G</td>
</tr>
<tr>
<td>Water Cooled</td>
<td>W</td>
<td>Remote condenser</td>
<td>T</td>
<td>Reverse Cycle</td>
<td>R</td>
<td>Non ducted</td>
<td>N</td>
<td>Other type</td>
<td>O</td>
</tr>
</tbody>
</table>

### 3.2 Energy analysis

The aim of ProMot is to examine energy consumption and propose the most energy efficient equipment, to serve cooling and heating loads. A simple relation to be used for energy consumption (E) is:

\[
E = \frac{P_c}{EER_{FL}} \cdot t_{FL,cool} + \frac{P_h}{COP_{FL}} \cdot t_{FL,heat} + \sum_i \left( \frac{P_{c,PL_i}}{EER_{PL_i}} \cdot t_{PL_i,cool} + \frac{P_{h,PL_i}}{COP_{PL_i}} \cdot t_{PL_i,heat} \right)
\]

(1)

where \( P_c \) and \( P_h \) are the net cooling and heating capacities (kW) respectively, \( t \) is the operating time (hrs/yr) and the subscripts FL and PL denote full and part load.

Typically one would discretise time of operation to intervals (i) such as 25-50%, 50-75% and 75-100% and sum the energy consumed during these intervals.
Equation 1 contains more parameters than currently available in the Eurovent database and requires knowledge of operating times in various power range regions. Part load efficiencies are not yet available by Eurovent, but it is foreseen to be included in the data at a later point in time, within the timeframe of the project. Full load efficiencies may be different than part load ones, depending on a number of chiller characteristics, such as the number and type of compressors, their part load efficiency, existence of inverter controls, sizing of condensers etc. On the other hand, operating hours of the heat pump are difficult to define, especially when in cooling mode. In contemporary chiller systems, operating time for compressors, is registered and can be retrieved from the chiller electronic control devices.

A simplified approach to equation (1) would be:

\[
E = \frac{P_c}{EER} \cdot t_{EFL,\text{cool}} + \frac{P_h}{\text{COP}} \cdot t_{EFL,\text{heat}}
\]  

where \( t_{EFL} \) is equivalent full load hours for heating or cooling. The assumption is that EER and COP do not vary greatly under part load operation.

In case time operation of the compressors of the chiller is unknown, for Greece the rule of thumb used is the equivalent full load hours \( t_{EFL} = 0.67 \cdot t_{\text{cool}} \) or \( t_{\text{heat}} \), with \( t_{\text{cool}} = 1100 \) hrs/yr and \( t_{\text{heat}} = 1300 \) hrs/yr. Although there is a degree of approximation in the equation above, it must be noted that it is intended for comparative study between two similar chillers, using the same approximations.

Currently the module has been programmed using equation (2). Once part load efficiency data is available in the database, equation (1) will be used.

### 3.3 Water cooled systems

Water Cooled Systems have undoubtedly higher energy efficiency ratio (EER) than the Air Cooled ones. On the other hand in Water Cooled Systems, incorporating cooling towers, the parameter of water consumption should be estimated and taken into account. Water is commonly used as a heat transfer medium to remove heat from the refrigerant condensers or industrial process heat exchangers. In the past, this was accomplished by using a continuous stream of water - from a utility water supply or a natural body of water – which was then discharged directly to a sewer or returning it to the body of water. Nowadays the cost of utility supply water has become prohibitively expensive. On the other hand, ecological disturbance could make the usage of water from natural body (e.g. lake) under certain conditions unacceptable (ASHRAE 2004).

Cooling towers overcome this problem by circulating water and they require a small fraction of the water otherwise needed with a once-through cooling system (ASHRAE 2004, Thumann 1987). The water consumption in a Cooling Tower is needed basically to replace water losses from evaporation and to safeguard the Tower from the concentration of dissolved solids and other impurities in the water.
According to (Rosaler 1995) the water losses which include evaporation, drift (water entrained in discharge vapour), and blowdown (water released to discard solids) could be estimated as the sum of Drift Losses, Evaporation Losses and Blowdown Losses.

Drift losses constitute a small ratio to the total losses of water. Besides, a portion of them can be subtracted from the necessary blowdown. These losses are estimated between 0.1 and 0.2%. Recent technology drift eliminator systems have managed to limit the drift rate to less than 0.001% of the recirculating water rate. Evaporation losses have decreased with improved design over the years. The evaporation rate from some Cooling Tower’s Manufactures manuals was estimated to be between 1.6% and 1.25%. ASHRAE (ASHRAE 2004) considers the evaporation rate at typical design conditions approximately 1% of the water flow rate for each 5.5 ºC of water temperature range. The blowdown losses depend on the concentration of dissolved solids in water and range between 0.3 and 4% of the water flow rate (Briganti 1994).

Estimation of total losses rate the values given in bibliography ranges from 3.8% to 1.33% of the water flow. The rate of 3.8% was found in a 1977 edition reference, therefore it is considered too high for the Cooling Towers in the market.

From the above we suggest that a typical default rate of water consumption in modern Cooling Towers to be used in our software is 1.5% of water flow through the tower. This value could be changed, should the user have a different estimate for the application at hand.

3.4 Chiller Economic Analysis

Economic analysis for comparison of alternative investments requires an understanding of several issues. The three most important elements to consider are (i) the investment costs for the systems, (ii) energy costs over the expected life of the chiller, and (iii) maintenance costs (including standstill costs) over the life of the chiller.

There are two general categories for economic analysis. Simple payback analysis and detailed economic analysis (LCC: life-cycle cost analysis). A simple payback analysis reveals options that have short versus long payback, whereas LCC calculates the total cost of each alternative during its lifetime. Although the LCC technique allows a more accurate comparison, it requires the knowledge of detailed information such as present value factor and interest rate.

In the chiller module a simple payback analysis has been used to compare alternative chillers, as it requires fewer data from the user. LCC analysis could be incorporated at a later stage. For comparison of chiller systems, payback technique is applied as:

\[
\text{Payback (years)} = \frac{\text{investment cost}}{\text{energy savings – operating & maintenance costs}}
\]

(3)

In case of water cooled chillers with Cooling Tower, water consumption has to be accounted as operating cost.
4 Operational Aspects of the Software Tool

The main functions of the chillers module are:

- Allows users to retrieve information for all chillers stored in the database.
- Guide the user in the selection of a specific chiller satisfying user-defined criteria for a specific application.
- Identifying and ranking a number of chillers based on energy consumption for user defined heating/heating loads.
- Calculate the energy and cost savings under different scenarios.

Figure 3.a presents the home page of the tool. Two destination buttons give access either to the Chiller Selector or to the Chiller Savings Analysis sub-module. The two sub-modules contain different program features or functions.

The Chiller Selector sub-module (Figure 3.b) provides parameters for selecting and sorting lists of chillers from the database. The available query parameters are those presented in Table 1 as well as the desirable range of cooling and heating capacities. The user can also select chillers from all manufacturers or from one or any combination of selected manufacturers. Detailed information for a specific chiller can be obtained clicking on its model name.

The Chiller Savings Analysis sub-module is used to calculate the annual reduction in energy use and monetary savings given that the user selects a specific Efficient Chiller.
instead of a standard one for a particular application. It enables the user to identify the most cost-effective alternative under three different scenarios:

1. **New (Compare New Chillers)** compares the costs of acquiring and operating a new standard chiller with those of an efficient model. A standard chiller is assumed to be the "base case". The module determines the energy and cost savings achievable due to purchase of the higher over a lower efficiency chiller model. Then, assuming that the efficient chiller is also more expensive to purchase, it determines the simple payback on the investment in the efficient chiller.

2. **Refurbishment (Repair versus New Motor Purchase)** compares the cost-effectiveness of rewinding a standard chiller against the cost of purchasing a new efficient model. This comparison takes into account a reduced efficiency for the rewound chiller attributable to age and rewind losses.

3. **Replace Existing (Replace Operable Chiller)** analyzes the cost-effectiveness of replacing an operable standard chiller with a new efficient model. This scenario is used to decide if it is cost-effective to immediately replace older, low-efficiency, rewound, and oversized and under-loaded chillers. The analysis considers the entire new chiller purchase price plus installation costs as the chiller price premium when determining the simple payback.

The Chiller Savings Analysis page is designed with two tabs: the Chiller Characteristics tab and the Costs/use tab. The Chiller Characteristics tab (Figure 4.a) allows the user to specify a chiller by entering descriptors, operating parameters and performance values. Values for the standard chiller are entered in the left column. Corresponding values for the efficient chiller are entered in the right-hand column. The user can select the efficient chiller from the database using the Chiller Selector sub-module.

![Figure 4: The Chiller Savings Analysis sub-module](image)
Information necessary for completion of a chiller energy savings analysis are entered at the data entry boxes on the Costs/use tab (Figure 4.b). These include purchase/installation cost, O&M cost as well as data concerning the price of energy and water. Energy and cost savings are shown in the Savings window at the bottom of the Chillers Savings Analysis page.

5 Conclusions

Computer-based tools that perform energy analysis of motor systems are extremely useful. ProMot is a decision support tool aiming to aid end-users to explore the possibility of energy savings in electricity driven motor systems of an industrial or tertiary installation. The main characteristics of the tool were presented and emphasis was given to the Chillers module. This module is a web-based application, helping energy consultants, chiller distributors and end users in planning and carrying out energy management and chiller efficiency improvement actions. The ProMot tool, can currently be found at www.motorchallenge.ch:8181/promot and will be hosted on the web by the Joint Research Centre – DG JRC, upon completion of the current project.

6 References


Tanner Ronald: “ProMot Pump module: Helping to find the most efficient Saving Actions for Pump systems” EEMODS 2005.


Exploitation Cost and Proper Choice of Low Voltage Induction Motors

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Abstract

The low voltage induction motor is regarded as a cheap product. Its purchase price balances its running cost in 2-3 months. Calculations of total cost of operation of induction motors (purchase and running costs) are shown. Cost calculation examples for standard and high efficiency (HE) motors (Poland made) ranging 0.75 through 160 kW are given. The calculations show that increased purchase cost of HE motors is often compensated in 200÷300 working hours.

The problem of “repair or replace” is evaluated as well. A common practice is to repair all damaged motors, regardless the repair cost, up to approx. 22 kW, compared with purchase price of a new motor. So, why are motors repaired again and again? Why are HE motors hardly ever installed? The author suggests that the voluntary agreement (CEMEP) is not a strong enough factor to change human routine.

1 Introduction

The three phase low voltage induction squirrel cage motor is regarded as a cheap product. Its purchase price balances its running cost in 2-3 months when operating continuously 8 hours per day, at or near full load. At 24 hours per day of operation a motor’s purchase price is lower than the cost of one month of operation. If motors are so cheap, comparing with operation costs why are low efficiency motors still bought and installed?

The exploitation cost of an induction motor consists of the purchase cost and the cost of the electricity consumed by the motor. The majority of the electricity is transformed into mechanical power available at the motor’s shaft, while some of electrical energy is lost as heat. The value of energy loses is determined by an efficiency factor $\eta$ shown on the motor’s nameplate and in a catalogue. The efficiency factor $\eta$ is equal to the ratio of useful mechanical power available on the shaft to the electrical power consumed by the motor. The efficiency of an induction motor is relatively high (much higher than the efficiency of a diesel engine and often higher than the efficiency of the driven machine), but taking into consideration that electrical motors are used in all branches of industry as well as in agriculture and in house applications the amount of wasted energy is huge. It is estimated that only in Poland, the value of energy losses in induction motors reaches 375 million Euro per year [1].

During the past two decades many projects and regulations were undertaken to reduce environment pollution by lowering the consumption of electricity. Such a goal can be reached by reducing loses in electrical motors i.e. installation and use of HE motors instead of standard motors.

In Europe since 1999 three classes of motor efficiency were set: Eff1 for HE, Eff2 for standard, and Eff3 for low efficient motors. Since above mentioned voluntary agreement of CEMEP and the classification of motors is not obligatory, in Europe the purchase and exploitation of HE motor is not popular. But is should be, as is shown below. If users do not appreciate HE motors, which causes useless energy consumption and environment pollution, they should be forced by law to install HE motors (as in the US and Canada).

2 Situation in Poland

In Poland motors of two efficiency classes (Eff1 and Eff2) are manufactured (Figure 1). Standard motors of Sg type (and similar) have efficiency factors in the area of Eff2-these motors are the most popular low voltage motors.

HE motors require higher volume of copper, aluminium and electro-technical steel, than standard motors and careful production process as well as final quality check is required, HE motors are more expensive than standard ones.

Figure 1: European efficiency classes and efficiency of motors type Sg and SEE manufactured in Poland
Customer have to choose what type of motor (Eff1 or Eff2) is worth purchasing. In Poland due to higher price of HE motors the Eff1 motors are seldom bought. Customers do not bother about the exploitation cost during the lifetime of low voltage motors, in most cases only the purchase cost is taken into consideration [3]. Tabulated costs of exploitation of different motors clearly enable customers to decide which motor (Eff1 or Eff2) they should choose. For proper choice the information concerning the total amount of working hours of the motor per year is necessary.

3 The calculation of joint motor use cost

The joint motor exploitation cost $K_u$ is composed of a motor purchase cost $K_m$ and a cost of electricity $K_e$ in whole period of use, which is $n$ years

$$K_u = K_m + K_e$$

The electric power cost in year one $K_a$ is defined, with $h$ hours of motor work per year, average load $p$- relation of the actual load to the nominal output, efficiency $\eta_p$ and the average electricity price (including fixed charges) $c_e$

$$K_a = \frac{h p \eta_p c_e}{\eta_p}$$

A cost of electricity power $K_a$ consumed in next $k$ years by the motor is reduced to one year with the discount rate $s$ (%)

$$K_k = \frac{K_a}{q^k}$$

where

$$q = 1 + \frac{s}{100}$$

The joint electric power cost in $n$ years period of motor use is

$$K_e = \sum_{k=1}^{k=n} K_k = \frac{K_a}{d}$$

where $d$ is called the depreciation rate

$$d = \frac{q^n (q-1)}{q^n - 1}$$
4 Calculation examples

Tables 1 and 2 contain examples of calculations of the annual costs of electric power use and joint use costs of low voltage standard motor 2p=4 (Eff2, Sg series) and HE motors (Eff1, SEE series) output 0,75-160 kW for 200, 1200, 4000, 6000 working hours per year. Evidence taken to calculations:

- average electric power price (low voltage) $c_e=0,062 \text{ €} / \text{kWh}$
- discount rate $s = 6\%$
- average power rate for a motor $p=0,75 P_N$
- motor’s lifetime $n=15$ years

Tabulated data shows that the cost of electricity is a main component of the motor use cost. Increased purchase cost of HE motors with raised efficiency in majority cases is compensated after 200-300 hours of the motor use. With continuous duty (6000 hours per year) the joint HE motors exploitation cost can be lower for about 10% than the joint standard motor use cost.

Table 1: Standard motors 1500 rpm

<table>
<thead>
<tr>
<th>Nominal output $P_N$ kW</th>
<th>efficiency $\eta_{0.75}$ %</th>
<th>Purchase price $K_m$ €</th>
<th>Annual energy cost at 200, 1200, 4000, 6000 operating hours per year €</th>
<th>Total exploitation cost at 200, 1200, 4000, 6000 operating hours per year €</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.75</td>
<td>71.0</td>
<td>43</td>
<td>10 59 195 293</td>
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</tr>
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<td>80.0</td>
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<td>21 104 347 521</td>
<td>260 1062 3419 5104</td>
</tr>
<tr>
<td>3.0</td>
<td>83.1</td>
<td>75</td>
<td>34 201 669 1003</td>
<td>400 2021 6561 9804</td>
</tr>
<tr>
<td>7.5</td>
<td>87.8</td>
<td>127</td>
<td>79 475 1583 2374</td>
<td>895 4733 15479 23156</td>
</tr>
<tr>
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<td>223 1339 4464 6696</td>
<td>2606 13431 43742 65393</td>
</tr>
<tr>
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<td>300 1802 6008 9012</td>
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</tr>
<tr>
<td>45</td>
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<td>442 2652 8840 13260</td>
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<tr>
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</tr>
<tr>
<td>132</td>
<td>94.4</td>
<td>2569</td>
<td>1295 7772 25906 38860</td>
<td>15127 77961 253861 379508</td>
</tr>
<tr>
<td>160</td>
<td>95.0</td>
<td>2777</td>
<td>1560 9360 31202 46804</td>
<td>17970 93632 305496 456836</td>
</tr>
</tbody>
</table>
Table 2: High efficiency motors, 1500 rpm

<table>
<thead>
<tr>
<th>Nominal output $P_n$ kW</th>
<th>Efficiency $\eta_{0.75}$ %</th>
<th>Purchase price $K_m$ €</th>
<th>Annual energy cost at 200, 1200, 4000, 6000 operating hours per year €</th>
<th>Total exploitation cost at 200, 1200, 4000, 6000 operating hours per year €</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.75</td>
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<td>68</td>
<td>8 50 167 250</td>
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</tr>
<tr>
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<td>109</td>
<td>16 98 327 491</td>
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</tr>
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</tr>
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</tr>
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<td>13570 65364 209619 313935</td>
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<td>3471</td>
<td>1552 9311 31037 46555</td>
<td>18523 93787 304526 455053</td>
</tr>
</tbody>
</table>

**BOLD** letters indicate examples when installing HE motor instead of standard one is recommended and profitable

## 5 Repair or replace electric motors?

Economic results of unexpected motor failure can be very severe but often difficult to calculate. Service workers try to put the driven machine back to normal work as fast as possible (with minimal costs).

Repairing motor is usually the routine. Meanwhile for smaller motors – of output up to 22 kW, cost of repair and cost of purchase of a new motor are more or less the same. For bigger motors, costs of repair amount to 50-60% of motor price.

Taking a decision to repair means loss of chance to install modern and cheaper in use HE motor, which is at the same time more a reliable product. While repairing, efficiency of the motor is usually decreased, so cost of the exploitation of the repaired motor grows [4].

Table 3 contains comparison of exploitation cost for “repair” or “exchange” options for typical low voltage standard motors 2p=4 series Sg (manufactured in Poland), of output 22, 75, 160 kW.
Table 3: Comparison of repair and replace (exchange) costs of 4 pole motors (in Poland)

<table>
<thead>
<tr>
<th>Nominal output P_N kW</th>
<th>option: Repair Exchange</th>
<th>Repair and purchase cost €</th>
<th>Efficiency decrease Δη_{0.75} %</th>
<th>Efficiency η_{0.75} %</th>
<th>Incomes from utilisation €</th>
<th>Total working cost of 15 years' exploitation at 200, 1200, 4000, 6000 operating hours per year</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td>-</td>
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<td>-</td>
<td>8348, 44579, 146026, 218487</td>
</tr>
<tr>
<td></td>
<td>E</td>
<td>2647</td>
<td>-</td>
<td>95.1</td>
<td>127</td>
<td>9605, 45033, 144232, 215157</td>
</tr>
<tr>
<td>75</td>
<td>R</td>
<td>1897</td>
<td>0.4</td>
<td>94.6</td>
<td>-</td>
<td>17093, 93079, 305840, 457823</td>
</tr>
<tr>
<td></td>
<td>E</td>
<td>3471</td>
<td>-</td>
<td>95.5</td>
<td>165</td>
<td>18358, 93622, 304360, 454888</td>
</tr>
<tr>
<td>160</td>
<td>R</td>
<td>3471</td>
<td>-</td>
<td>95.5</td>
<td>165</td>
<td>18358, 93622, 304360, 454888</td>
</tr>
</tbody>
</table>

**BOLD** letters indicate examples when installing HE motor instead of repairing is recommended and profitable

**R** - repair of Sg type motor (winding and bearing replacement, balancing and painting).

**E** – scrap of Sg type motor, (utilization), replacing by motor SEE type.

Price of electricity: 61.8€ per 1MWh (at 400V network)

6 Conclusions

- The main component of low voltage motor exploitation cost is the electricity cost. The installation of a more expensive high efficient motor, with higher efficiency and lower losses, is balanced with adequate exploitation costs of standard motor after 200-300 hours of motor utilization.

- Although in most cases installing a HE motor instead of a standard one is profitable even at 300 working hours per year, calculation as shown above should be carried on at every time, since fore some motors even at 6000 hours the cost of exploitation of HE motor will be higher than for standard machine.

- Repairing and repeated use of failed low voltage motor can be reasonable only for higher power motors, working few hours per year. Repairing a motor of output less than 22 kW is entirely economically unreasonable.

- HE motors have reduced temperature rise of windings and bearings, so their lifetime should be longer than lifetime of standard motors.

- Despite the fact the installing HE motors is profitable for users and beneficial for environment HE motors are not popular. Because of higher price comparing to standard motors customers do not want to buy HE motors. Author suggest that voluntary agreement (CEMEP) is not enough strong factor to change human routine. An obligatory use of HE motors should be established.

- This paper does not deal with problem of accuracy of measuring motors’ efficiency. But accurate calculations of energy costs and profits require accurate method of efficiency establishing – method shown in IEC34-2 with stray load loses of 0.5% does
not allow users to be sure about the amount the of saved electricity. Author suggests that method based on measure of stray load loses should be prepared and set as obligatory in Europe.

References:

Energy Policy Act, 1992


A Local Initiative for Energy Efficiency Improvements in Motor Driven Systems in Public and Private Companies - Case Studies

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Abstract

In the Free and Hanseatic Town Hamburg reduction potentials in public buildings are developed systematically in the context of the energy management by standardised efficiency programs. The City has had special means ready for financing energy saving measures for many years, because the investments amortize themselves by the operation cost reduction.

Examples of efficient electrical motor systems in public buildings:
- ventilation facilities and air conditioning
- Heating pumps energy saving program

The City of Hamburg also offers a promotional program "Enterprises for Resource Protection" for private investors from the Hamburg economy. With this program voluntary investment measures are initiated in private enterprises by financial subsidies to conserving resources.

Examples of efficient electrical motor driven systems in enterprises:
- Mill: Speed controlled exhauster drives
- Spice mill: Speed controlled mill drives
- Printer: Efficient ventilation techniques at a paper exhaust system
- Wastewater treatment: Adjustable fans for pressure aerators
- Hazardous waste incineration plant: Optimisation of the SO₂-gas scrubbing system by mass flow controlled pumps

With these programs efforts to climate protection can be realised more economically.

1 Introduction

Today's electrical propulsion systems have, in most cases, a high efficiency. But, facilities are not always being operated in accordance with their own design, because often their consumption of electricity isn't taken into account.

By the application of modern process measurement and control systems and by an improved coordination of the drives used, the work processes and the technological facilities, the energy efficiency in the complete system can be made considerably better.

For more than 30 years the City of Hamburg has been realizing measures for increasing efficiency in the context of its climate protection policy on electrical drives in its own properties as well as also in the private area.

Every year earmarked funds are provided for the City's own properties to finance measures for the reduction of energy consumption. At the same time, further education programs are being offered for technical staff to improve the operating states of their facilities.
The main use of drives is in ventilation facilities and in heating pumps. In the efficiency programs a horizontal approach is being pursued.

Which means: A certain technology is replaced in as many properties as possible at the same time. By the common advertising of large quantities and extensive installation work substantially lower unit prices can be obtained, which increases the efficiency of the measures.

Concentrating on one technology bundles and improves know-how, standardises the planning performance and simplifies the execution. Through its promotional programs with their financial subsidies, the City influences private plant operators by making voluntary investments in resource protection more attractive.

There is a considerable amount of electric drives in the Hamburg trade companies. A promotional program "Enterprises for Resource Protection" has been set up specifically for this target group.

2 Efficient drive technology in the City’s own properties

2.1 Ventilation facilities and air conditioning

The City of Hamburg operates many buildings for special uses where rooms must be ventilated or in special cases also must be air conditioned (universities, schools, theatres, museums, hospitals, prisons, covered markets etc.). Systematic examinations show that in many cases the facilities have not been adapted to their purposes and aren't being operated in the best possible way either. Far too high air volumes are often being moved in the ventilation systems. The existing airflow regulations through by-passes and throttle valves have been replaced by energy saving variable speed drives.

In the standardised program the following criteria are generally being required to motor driven ventilation facilities to increase their energy efficiency:

- Operation of the drives only when necessary
- Adaptation of the capacities to the need
- Adaptation of the motor power to the required performance
- Use of speed regulated drives with variable airflows
- Use of high efficient motors (EFF1)

For example, the City of Hamburg has retrofitted the existing ventilation and air conditioning systems in 14 properties. By an investment of 2.7 million Euros a saving of electrical energy by 3.7 million kilowatt hours as well as a reduction of the connected power by 690 kilowatts have been achieved (Table 7, page 9).

Every year, the budget of the City is reduced recurrently through the reduced electrical energy consumption by more than 460,000 Euros operating costs. Thus the investments are profitable after about 6 years, when a simple economic calculation applies.
With the redevelopment of ventilation facilities, more often than not, an additional saving of heating energy will also occur which leads to a decrease of the payback period.

2.2 Heating pumps energy saving program

Measuring campaigns in Switzerland and in Germany prove that heating pumps are frequently oversized. Therefore these pumps need more electric power than necessary (on the average, two up to three times as much). Modern electronically regulated heating pumps can save up to 50 per cent of electric power. Old pumps can often be retrofitted with a modern technology.

A heating pump exchange was carried out, or available pumps were retrofitted with a speed control, in 34 public properties with investments of 358,000 Euros (Table 8, page 10). Thereby the installed driving power was reduced by 79 kW and therefore 584,000 kilowatt hours are being saved recurrently per annum. The investments are profitable with the reduction of costs of about 47,300 Euros after 8 up to 9 years (simple economic consideration).

Following this experiences the conditions were worked out for a more efficient heating pump exchange program. This heating pumps energy saving program was converted in a standardised program in 2004.

The present program concept is based on the use of high efficient heating pumps. However, this is carried out exclusively coupled with a hydraulic optimisation of the complete heat distribution. During the development different versions have been examined. These are different in their respective regulation concepts (e.g. only one main pump, pressure difference) or they use other command variables (e.g. temperature difference) for the load control.

The following questions arose during the development of the program concept:

- With which criteria can objects be summarised for the redevelopment of the heating pumps?
- What can be done so that an economic implementation gets possible?
- How can the required data be provided for a pump redevelopment (e.g. by exchanging boilers)?

An optimal energy saving with the pump exchange is being reached particularly after a thermal insulation measure has been implemented to the building. Because of the lower heat requirement an appropriately smaller heating system can be installed with smaller dimensioned heating pumps. Under these conditions the concept is being carried out by the following scheme:
(1) Finding suitable facilities (with a thermal insulated building cover)
(2) Recording of the production data
(3) Hydraulic optimisation of the heating system
(4) Choice of technology, dimensioning of the pumps
(5) Exchange of the pumps / refitting of the external control facilities, if necessary
rebuilding of the facilities

The heating systems of all buildings shall be retrofitted with a new insulation according
to these criteria in the future. As real examples the measures in the following 4 Ham-
burg schools are shown. The installed electrical input power in these examples was
reduced totally by 13.8 kilowatts and an amount of 79,000 kWh is saved per annum.

Table 1: Examples in schools

<table>
<thead>
<tr>
<th>School</th>
<th>Power reduction</th>
<th>Energy savings</th>
<th>Controlling principle</th>
</tr>
</thead>
<tbody>
<tr>
<td>High school “Willhöden”</td>
<td>3.7 kW</td>
<td>24 MWh/a</td>
<td>Mass flow</td>
</tr>
<tr>
<td>Comprehensive school “Winterhude”</td>
<td>2.2 kW</td>
<td>12 MWh/a</td>
<td>Mass flow</td>
</tr>
<tr>
<td>High school “Hummelsbüttel”</td>
<td>4.0 kW</td>
<td>22 MWh/a</td>
<td>Mass flow</td>
</tr>
<tr>
<td>Comprehensive school “Alter Teichweg”</td>
<td>3.9 kW</td>
<td>21 MWh/a</td>
<td>Pressure difference</td>
</tr>
</tbody>
</table>

Further energy savings at the heating energy have been arisen by the use of gas cen-
tral heating boilers with an upper heating value technology.

3 Examples of efficient electrical motor driven systems in enterprises

In the context of the Hamburg’s promotional program "Enterprises for Resource Protec-
tion" the senate of Hamburg initiates voluntary measures for energy savings, water
savings and raw material savings in Hamburg’s companies in cooperation with Ham-
burg’s economy. Improving the energy efficiency of motor driven systems like electric
machines, pumps, conveyers, ventilators and compressors is included in this program.

3.1 Mill / Bock & Schulte GmbH & Co.
Speed controlled exhauster drives

The enterprise Bock & Schulte is a complex service provider. The business objects
are subcontracting and refinishing of raw materials. The main lines of business are
grinding, mixing, sieving, and packing of minerals.
Two pendulum mills are the central facilities of the production line "milling". To get a defined grain size the mill material circulates in the pendulum mills. When the material is light enough, it is blown out through the exhausters. In the past, the air stream was controlled over throttle valves (flaps) in which the exhauster drives always went on with full power. This system wasn’t very energy efficient.

After the installation of speed controls (frequency regulator) it is now possible to adjust a certain speed for different mill materials. With this new speed controlled System the mill needs less electrical energy to run.

Table 2: Bock & Schulte

<table>
<thead>
<tr>
<th></th>
<th>Old facilities</th>
<th>New facilities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exhauster drive</td>
<td>Uncontrolled</td>
<td>Frequency controlled</td>
</tr>
<tr>
<td>Adjusting of the required air stream</td>
<td>Flap position</td>
<td>Number of revolutions</td>
</tr>
<tr>
<td>Saved kilowatt hours per annum</td>
<td>30,000 kWh</td>
<td></td>
</tr>
<tr>
<td>Saved costs per annum</td>
<td>3,000 €</td>
<td></td>
</tr>
<tr>
<td>CO2 avoidance per annum</td>
<td>18 t</td>
<td></td>
</tr>
</tbody>
</table>

3.2 Spice mill / Kastning & Petersen GmbH

Speed controlled mill drives

The company Kastning & Petersen is a manufacturer for spices and medicinal herbs as well as for other vegetable raw materials. At the processing and refining of vegetable raw materials different proceedings are used. The vegetable raw materials are processed in powder and blade mills to produce rough cut, fine cut and powder.

The processes were examined for possibilities of energy savings at the mill drives. The installation of frequency regulators and stored program controls (SPC) is an appropriate possibility.

Processing tests were carried out with and without SPC and frequency regulators to estimate the amount of energy savings. The result of the measures was that a complete energy saving of about 20% can be achieved.

One blade mill and one powder mill and its necessary centrifuges have together eighteen motors installed in two systems. These two mills have being attached to two new control systems. Each control regulates the optimal speeds of the connected drives. These speeds were found out in pre-tests for different mill materials.

The first operational experiences show that the product doesn’t heat up so strongly at the optimal mill speed. Through this the mill materials have being ground better and faster and it circulates in the mill during a shorter time. Already the first run yields a very high quota of ready goods.
Economic advantages have been arisen beyond the energy savings due to shorter times for processing and a better product quality.

Table 3: Kastning & Petersen

<table>
<thead>
<tr>
<th></th>
<th>Old facilities</th>
<th>New facilities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exhauster drive</td>
<td>Uncontrolled</td>
<td>Frequency controlled</td>
</tr>
<tr>
<td>Adjusting of the required air stream</td>
<td>None</td>
<td>Number of revolutions</td>
</tr>
<tr>
<td>Saved kilowatt hours per annum</td>
<td>53,000 kWh</td>
<td></td>
</tr>
<tr>
<td>Saved costs per annum</td>
<td>4,800 €</td>
<td></td>
</tr>
<tr>
<td>CO₂ avoidance per annum</td>
<td>33 t</td>
<td></td>
</tr>
</tbody>
</table>

3.3 Printer / Broschek Tiefdruck GmbH and its service provider Cleanaway Hamburg GmbH & Co. KG

Efficient ventilation techniques at a paper chip exhaust system

Cleanaway Hamburg is a disposal service provider at the printing company Broschek Tiefdruck. Broschek Tiefdruck operates Hamburg's largest printing company.

Paper chips which are arisen at the printing process are exhausted with the room air. Through a paper chips exhaust system large air quantities (35,000 m³/h) were led out to the atmosphere. The heat energy contained in it was wasted until now. In the context of a new conception for the production plant Cleanaway Hamburg invested in energy efficiency measures at the paper chip exhaust system.

A system change took place. Now the heat quantities contained in the output air are used again for heating the production hall. In addition, about 151,000 kWh of electricity per annum has been saved by the installation of a product unaffected ventilation technology, because this technique is much more energy efficient. Since implementing the new heat recovery and the efficient ventilation system in May 2004 the following energy savings and operating cost reductions have been obtained per annum.

Table 4: Cleanaway Hamburg

<table>
<thead>
<tr>
<th>Energy savings</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Saved kilowatt hours per annum (heat)</td>
<td>449,000 kWh</td>
</tr>
<tr>
<td>Saved kilowatt hours per annum (electricity)</td>
<td>151,000 kWh</td>
</tr>
<tr>
<td>Saved costs per annum</td>
<td>24,800 €</td>
</tr>
<tr>
<td>CO₂ avoidance per annum</td>
<td>185 t</td>
</tr>
</tbody>
</table>
3.4 Wastewater treatment / Hamburger Stadtentwässerung
Adjustable fans for pressure aerators

The Hamburger Stadtentwässerung performs sovereign tasks in Hamburg for the draining and cleaning of sewage in two wastewater treatment plants. In the plant "Dradenau" the final full biological cleaning of the sewage preconditioned on "Köhlbrandhöft" takes place.

The oxygen required for the biological cleaning process in the aeration basins is done via electrically driven surface aerators. The energy consumption is very high in ratio to the amount of oxygen brought in.

One of the 16 aeration basins was retrofitted to a pressure aerator for measuring purposes. With this aerator the air is blown into the sewage as fine bubbles through perforated tubes on the basin ground. This technology is very energy efficient and has a high reduction of the CO₂ emissions.

After this pre-test all the 16 basins will be retrofitted with a pressure aerator system corresponding to the results of the experiments. After all annual energy savings of about 17,000 MWh will be expected, according to CO₂ avoidance about 10,000 tons.

Table 5: Hamburger Stadtentwässerung

<table>
<thead>
<tr>
<th>Old facilities</th>
<th>New facilities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ventilating of the first of 16 aeration basins</td>
<td>Surface aerator</td>
</tr>
<tr>
<td>Saved kilowatt hours per annum</td>
<td>1,062,000 kWh</td>
</tr>
<tr>
<td>Saved costs per annum</td>
<td>70,000 €</td>
</tr>
<tr>
<td>CO₂ avoidance per annum</td>
<td>650 t</td>
</tr>
</tbody>
</table>

3.5 Hazardous waste incineration plant / AVG Abfall-Verwertungs-Gesellschaft mbH
Optimisation of the SO₂-gas scrubbing system by mass flow controlled pumps

The AVG Abfall-Verwertungs-Gesellschaft mbH offers the following services in its disposal centre: Special garbage incineration; chemically-physical treatment; separation of oil water mixtures; intermediate storage for waste; logistics and industry service.

To fulfil the environmental protection regulations the company operates an expensive flue gas scrubbing system for its incineration plant. The flue gas stream contains SO₂ gas. Cleaning the flue gas stream requires the SO₂ to be washed out by the addition of lime milk.
The electricity consumption of the pumps of the SO₂-gas scrubber was reduced considerably by installing more efficiently pumps and a new gas control system. Therefore the pumps are operated under control of the SO₂-gas flow and the SO₂-gas concentration.

The system has been energetically optimised and supplies now the required lime milk flow to fulfil the regulations. For the guarantee of a constant cleaning performance the gas scrubber is supervised by a computer-aided system.

Table 6: AVG Abfall-Verwertungs-Gesellschaft

<table>
<thead>
<tr>
<th>Energy savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saved kilowatt hours per annum (electricity)</td>
</tr>
<tr>
<td>Saved costs per annum</td>
</tr>
<tr>
<td>CO₂ avoidance per annum</td>
</tr>
</tbody>
</table>

Table 7: Retrofitting of ventilation and air conditioning systems in 14 properties (Energy, costs and power savings)

<table>
<thead>
<tr>
<th>No.</th>
<th>Building</th>
<th>Street</th>
<th>Zip</th>
<th>City</th>
<th>Investment</th>
<th>Elec. Energy</th>
<th>Costs</th>
<th>Power</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>University</td>
<td>Martin-Luther-King-Platz 6</td>
<td>20146</td>
<td>Hamburg</td>
<td>48,900.00 €</td>
<td>150,000 kWh/a</td>
<td>1,300.00 €</td>
<td>7.5 kW</td>
<td>1992</td>
</tr>
<tr>
<td>2</td>
<td>University</td>
<td>Martin-Luther-King-Platz 8</td>
<td>20146</td>
<td>Hamburg</td>
<td>25,194.42 €</td>
<td>100,000 kWh/a</td>
<td>6,544.00 €</td>
<td>7.0 kW</td>
<td>1996</td>
</tr>
<tr>
<td>3</td>
<td>Central market</td>
<td>Bankstraße 1</td>
<td>20097</td>
<td>Hamburg</td>
<td>206,075.17 €</td>
<td>286,200 kWh/a</td>
<td>19,322.00 €</td>
<td>39.0 kW</td>
<td>1997</td>
</tr>
<tr>
<td>4</td>
<td>University</td>
<td>Bundesstraße 55</td>
<td>20146</td>
<td>Hamburg</td>
<td>373,342.00 €</td>
<td>427,490 kWh/a</td>
<td>34,614.00 €</td>
<td>80.0 kW</td>
<td>1997</td>
</tr>
<tr>
<td>5</td>
<td>Museum</td>
<td>Ochsenhorststraße 18</td>
<td>20005</td>
<td>Hamburg</td>
<td>537,051.53 €</td>
<td>1,015,000 kWh/a</td>
<td>173,906.00 €</td>
<td>252.0 kW</td>
<td>1998</td>
</tr>
<tr>
<td>6</td>
<td>University</td>
<td>Von-Melle-Park 3, 5, 9</td>
<td>20146</td>
<td>Hamburg</td>
<td>406,050.44 €</td>
<td>530,000 kWh/a</td>
<td>40,903.00 €</td>
<td>34.0 kW</td>
<td>1996</td>
</tr>
<tr>
<td>7</td>
<td>Hospital</td>
<td>Lohnhorststraße 5</td>
<td>20097</td>
<td>Hamburg</td>
<td>109,927.75 €</td>
<td>374,000 kWh/a</td>
<td>25,053.00 €</td>
<td>45.0 kW</td>
<td>1997</td>
</tr>
<tr>
<td>8</td>
<td>University</td>
<td>Banhofstraße 28</td>
<td>20146</td>
<td>Hamburg</td>
<td>153,388.00 €</td>
<td>424,460 kWh/a</td>
<td>23,698.00 €</td>
<td>34.0 kW</td>
<td>2000</td>
</tr>
<tr>
<td>9</td>
<td>University</td>
<td>Von-Melle-Park</td>
<td>20146</td>
<td>Hamburg</td>
<td>127,822.97 €</td>
<td>34,190 kWh/a</td>
<td>60,149.00 €</td>
<td>36.0 kW</td>
<td>2002</td>
</tr>
<tr>
<td>10</td>
<td>Trade school</td>
<td>Billwerder Böde 614</td>
<td>21033</td>
<td>Hamburg</td>
<td>11,878.69 €</td>
<td>4,240 kWh/a</td>
<td>406.00 €</td>
<td>0.9 kW</td>
<td>2003</td>
</tr>
<tr>
<td>11</td>
<td>Library</td>
<td>Schlüterstraße 28</td>
<td>20146</td>
<td>Hamburg</td>
<td>18,950.00 €</td>
<td>17,000 kWh/a</td>
<td>1,474.00 €</td>
<td>4.0 kW</td>
<td>2003</td>
</tr>
<tr>
<td>12</td>
<td>University</td>
<td>Martin-Luther-King-Platz 6</td>
<td>20146</td>
<td>Hamburg</td>
<td>540,420.00 €</td>
<td>87,000 kWh/a</td>
<td>49,986.00 €</td>
<td>16.0 kW</td>
<td>2003</td>
</tr>
<tr>
<td>13</td>
<td>Heine Museum</td>
<td>Ferdinandstr. 1</td>
<td>20099</td>
<td>Hamburg</td>
<td>50,000.00 €</td>
<td>163,000 kWh/a</td>
<td>11,540.00 €</td>
<td>9.5 kW</td>
<td>2003</td>
</tr>
</tbody>
</table>

Total | 2,689,407.67 € | 3,699,310 kWh/a | 457,331.00 € | 689 kW |
Table 8: Heating pump exchange in 34 public properties (Energy, costs and power savings)

<table>
<thead>
<tr>
<th>No.</th>
<th>Building</th>
<th>Street</th>
<th>Zip</th>
<th>City</th>
<th>Investment</th>
<th>Elec. Energy</th>
<th>Costs</th>
<th>Power</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Administrative building</td>
<td>Neugrabener Markt 5</td>
<td>21149</td>
<td>Hamburg</td>
<td>12,548.32 €</td>
<td>19,000 kWh/a</td>
<td>2,300.00 €</td>
<td>3.0 kW</td>
<td>1994</td>
</tr>
<tr>
<td>2</td>
<td>University</td>
<td>Martin-Luther-King-Platz 6</td>
<td>20146</td>
<td>Hamburg</td>
<td>5,013.51 €</td>
<td>18,870 kWh/a</td>
<td>1,930.00 €</td>
<td>2.8 kW</td>
<td>1994</td>
</tr>
<tr>
<td>3</td>
<td>University</td>
<td>Martin-Luther-King-Platz 6</td>
<td>20146</td>
<td>Hamburg</td>
<td>8,529.86 €</td>
<td>15,660 kWh/a</td>
<td>1,433.00 €</td>
<td>1.9 kW</td>
<td>1995</td>
</tr>
<tr>
<td>4</td>
<td>University</td>
<td>Martin-Luther-King-Platz 6</td>
<td>20146</td>
<td>Hamburg</td>
<td>2,613.37 €</td>
<td>8,750 kWh/a</td>
<td>628.00 €</td>
<td>0.0 kW</td>
<td>1995</td>
</tr>
<tr>
<td>5</td>
<td>Comprehensive school</td>
<td>Ladenbeker Weg 13</td>
<td>21033</td>
<td>Hamburg</td>
<td>12,909.03 €</td>
<td>23,490 kWh/a</td>
<td>2,918.00 €</td>
<td>3.6 kW</td>
<td>1995</td>
</tr>
<tr>
<td>6</td>
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<td>3,835.77 €</td>
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<td>830.00 €</td>
<td>1.1 kW</td>
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<td>8,241.00 €</td>
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<td>7,459.75 €</td>
<td>9,180 kWh/a</td>
<td>992.00 €</td>
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<td>14,298.90 €</td>
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<td>3,338.00 €</td>
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<td>10</td>
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<td>5,112.92 €</td>
<td>10,500 kWh/a</td>
<td>767.00 €</td>
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<td>11</td>
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<td>22371</td>
<td>Hamburg</td>
<td>5,726.00 €</td>
<td>7,700 kWh/a</td>
<td>690.00 €</td>
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<td>3,323.00 €</td>
<td>7,700 kWh/a</td>
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<td>Hamburg</td>
<td>5,726.00 €</td>
<td>7,710 kWh/a</td>
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<td>Tower block</td>
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<td>60,000.00 €</td>
<td>93,000 kWh/a</td>
<td>8,085.00 €</td>
<td>15.0 kW</td>
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<td>19</td>
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<td>Tornquaststraße 60</td>
<td>20259</td>
<td>Hamburg</td>
<td>9,308.79 €</td>
<td>3,250 kWh/a</td>
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<td>20253</td>
<td>Hamburg</td>
<td>3,920.33 €</td>
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<td>8,547.00 €</td>
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<td>858.00 €</td>
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<td>22159</td>
<td>Hamburg</td>
<td>28,983.53 €</td>
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<td>24</td>
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<td>2.0 kW</td>
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<td>1998</td>
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<td>21075</td>
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<td>8,000 kWh/a</td>
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<td>1.9 kW</td>
<td>1999</td>
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<td>34</td>
<td>Museum</td>
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<td>12,000 kWh/a</td>
<td>643.00 €</td>
<td>1.9 kW</td>
<td>2000</td>
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<td>Total</td>
<td></td>
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<td>358,794.40 €</td>
<td>584,200 kWh/a</td>
<td>47,387.00 €</td>
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Volume II

Motor System Audit and Software Tools II
A Local Initiative for Energy Efficiency Improvements in Motor Driven Systems
Abstract

Previous studies carried out in Europe showed that there is widespread oversizing of electric motors, both in industry and in buildings. Oversized three-phase induction motors operate with lower efficiency and power factor. Motor oversizing is by far the most important cause of poor power factor in industrial installations. In some situations, motor performance can be improved both in terms of efficiency and power factor through winding connection change from delta to star. A practical method is proposed to quickly and easily evaluate when the delta to star change is appropriate in terms of efficiency for three-phase squirrel-cage induction motors designed to operate at the nominal power with delta connection and with access to the six winding terminals. It is particularly suitable to industrial plants, where, typically, most of the electric motor systems are oversized, particularly in the low power range. If the user applies the described method to grossly oversized motors and/or driving high inertia low duty-cycle loads, the active and reactive electrical energy bill can be reduced. When driving centrifugal loads with grossly oversized motors additional savings are possible, due to the lower operation speed of the motor.

1 Introduction

In industry, more than 90% of the electrical motors are three-phase squirrel cage induction motors (IMs) [Almeida, 2000]. In the European Union, the average load factor for electric motors in both industrial and tertiary sectors is 0.57. However the average load factor per power range in some sectors can be as low as 0.25 [Almeida, 2000]. Individual motors in those ranges have even lower load factors.

Motor oversizing is mainly due to poor motor system design, most likely due to the gross overestimation of the mechanical power required by the load [Almeida, 2000]. These situations lead to a reduction of the IM efficiency ($\eta$) and of its power factor ($\lambda$). However, for specific conditions, the stator winding connection permanent change from delta (D) to star (Y) can significantly improve both the efficiency and the power factor. Obviously, that possibility is only available for IMs designed to operate at the nominal power with D connection and with access to the 6 winding terminals.

In this paper, a field evaluation method to assess the most appropriate IM stator winding connection is proposed, requiring only low-cost and easy-to-use equipment (a stroboscopic tachometer and a voltmeter). The proposed method can be integrated in the group of low-cost measures with a significant energy savings potential. The importance of this work is highlighted by the recent concerns about electric motor systems optimization in both industrial and tertiary sectors.
2 Simulated Results

The efficiency-load factor curves for 3 different IMs were simulated in the Simulink (MATLAB) software using the per-phase equivalent circuit (Figure 1). The per-phase equivalent circuit parameters were obtained from laboratorial tests for the 3 kW IM. For the 11 kW and 300 kW IMs the per-phase equivalent circuit parameters were obtained from book data in [Alger, 1969] and [Beaty, 1998], respectively. In Figure 2, the efficiency-load factor curves for both D and Y connections for the 3 simulated IMs can be seen. In the Y connection, a voltage 1.73 times lower than the voltage considered in the D connection was considered in the simulation.

The interception point load factor (point $\alpha$) between the efficiency-load factor simulated curves for D and Y connections is 0.34, 0.42 and 0.48 for the 3 kW, 11 kW and 300 kW IMs, respectively.

![Per-phase equivalent circuit used for simulations](image1)

**Figure 1:** Per-phase equivalent circuit used for simulations

![Simulated efficiency-load factor curves for 3 different IMs](image2)

**Figure 2:** Simulated efficiency-load factor curves for 3 different IMs: (a) 3 kW, 4 poles, f=50 Hz, $R_1=8.2 \, \Omega$, $R_2=7.2 \, \Omega$, $L_1=L_2=0.0052 \, H$, $R_c=4187 \, \Omega$, $L_m=0.535 \, H$, $V_1=400 \, V$ for D connection and $V_1=231 \, V$ for Y connection; (b) 11 kW, 4 poles, f=60 Hz, $R_1=R_2=0.15075 \, \Omega$, $L_1=L_2=0.000666 \, H$, $R_c=83.75 \, \Omega$, $L_m=0.026658 \, H$, $V_1=127 \, V$ for D connection and $V_1=73 \, V$ for Y connection and (c) 300 kW, 6 poles, f=60 Hz, $R_1=0.0073 \, \Omega$, $R_2=0.0064 \, \Omega$, $L_1=L_2=0.000159 \, H$, $R_c=35 \, \Omega$, $L_m=0.00663 \, H$, $V_1=254 \, V$ for D connection and $V_1=147 \, V$ for Y connection.
3 Experimental Results

The testing facility used to test the IMs, fulfils the IEEE 112 standard requirements [Almeida, 2005].

Thirteen totally-enclosed fan-cooled IMs of five different brands (denominated in this paper by A, B, C, D and E) were tested, with nominal power between 185 W and 7.5 kW. All the IMs have 4 poles, except two, one with 2 and the other with 6 poles.

In all the tests the temperature stability (temperature changes lower than 0.1ºC per minute) was guaranteed between 75% and 100% of full-load.

The motor efficiency (measured by direct method) is given by (1), where \( T \) is the torque, \( \omega \) is the speed, \( P_{elec} \) is the input active electrical power, and \( P_{mech} \) is the output mechanical power (useful power).

\[
\eta = \frac{P_{mech}}{P_{elec}} = \frac{T \cdot \omega}{P_{elec}} \quad (1)
\]

The motor load factor (\( \psi \)) is given by (2), where \( P_N \) is the motor nominal power.

\[
\psi = \frac{P_{mech}}{P_N} \quad (2)
\]

The experimental results are presented in Figs. 3 and 4. In Figs. 3a and 3b the efficiency-load factor curves can be seen for Y and D connections. For a load lower than interception point (point \( \alpha \)) the Y connection efficiency is higher than D connection efficiency.

For the considered IMs, the point \( \alpha \) has no regular relation with brand, nominal power, number of poles, and it is between \( \psi = 0.27 \) and \( \psi = 0.43 \) (average \( \psi = 0.36 \)). For 10 of the 13 tested motors, if the load factor is equal or less than \( \psi = 0.33 \), the Y connection efficiency is higher than D connection efficiency. Although this was only validated for 10 IMs with power between 185 W and 7.5 kW, it can be applied in all IMs. In fact, for IMs with higher power, the limit \( \psi = 0.33 \) is also valid because the point \( \alpha \) moves to higher load factors due to the flatter efficiency and to the typical shift of the maximum efficiency operating point to the rated load. In fact, for most low power IMs the maximum efficiency load factor is between 75-90%, and for most medium-large power IMs the maximum efficiency load factor is between 90-100%.

The experimental value for point \( \alpha \) for the 3 kW IM (Brand A), is approximately in accordance with the simulated result obtained in Section 2 (note that the effect of temperature variation between the D and Y operation is not considered in the simulation).

It can be concluded that the load factor can be used as an indicator for the connection change decision. However, it is difficult to obtain in the field the exact load factor due to the difficulties associated with the torque measurement process.

IM oversizing also leads to a very significant power factor decrease. The D to Y change leads to a significant power factor improvement, as it can be seen in Figure 4a.
For any load factor, the D to Y change also leads to a speed decrease, as it can be seen in Figure 4b.

Figure 3:  (a) Efficiency-load factor curves (IMs with $P_N \geq 2.2$ kW); (b) Efficiency-load factor curves (IMs with $P_N < 2.2$ kW)

Figure 4:  (a) Power factor-load factor curves (all IMs); (b) Speed-load factor curves (4-pole IMs)

From Figs. 3 and 4, it can be concluded that the user should evaluate several factors before changing the winding connection. The most important factor should be the efficiency, because the power factor and the slip ($s$) are always higher for the Y connec-
tion. The point \( \alpha \) determination can be based on factors easily obtained in the field and with a reduced brand dependency level.

4 Determination of Point \( \alpha \)

In the absence of voltage unbalance and of IM electromechanical asymmetries, the active electrical power (\( P_{\text{elec}} \)) absorbed by the IM is given by (3), where \( V_{ll} \) is the line-to-line voltage, \( I_l \) is the line current and \( \lambda \) is the power factor.

\[
P_{\text{elec}} = \sqrt{3} \cdot V_{ll} \cdot I_l \cdot \lambda
\]

(3)

When the winding connection is changed from D to Y, the winding voltage decreases 1.73 times. In the point \( \alpha \) the efficiency, the mechanical power and the active electrical power values for both D and Y connections are equal (see (1) and (2)). In the point \( \alpha \), the relation (4) is true.

\[
\frac{I_{l(D)}}{I_{l(Y)}} = \frac{\lambda_{Y}}{\lambda_{D}}
\]

(4)

Some IM field measurements and nameplate values (nominal values) based indicators were searched, namely, line-to-line voltage, line current and speed or slip based indicators. These values are easily obtained in the field, using common measurement devices (voltmeter, clamp ammeter and stroboscopic tachometer). To guaranty a good accuracy level in the voltage and current measurement, true rms (rms values calculated by digital integration) devices should be used. In the proposed method, the measurement of the power factor is avoided because it requires the use of a power factor measurement device, wattmeter or power analyzer, which, to have sufficient accuracy, are expensive.

Four indicators are analysed: 2 line current based (\( K_{i1} \) and \( K_{i2} \)) and 2 slip based (\( K_{s1} \) and \( K_{s2} \)). The indicators \( K_{i1}, K_{i2}, K_{s1} \) and \( K_{s2} \) are related to point \( \alpha \) and defined by (5), (6), (7) and (8), where \( I_N \) is the nominal line current, \( V_N \) the nominal line-to-line voltage, \( V_{\text{meas}} \) is the measured line-to-line voltage, \( s_N \) is the nominal slip and \( s_{\text{meas}} \) is the measured slip.

\[
K_{i1} = \frac{I_{l(D)}}{I_N}
\]

(5)

\[
K_{i2} = \frac{I_{l(Y)}}{I_{l(Y)}}
\]

(6)

\[
K_{s1} = \left( \omega_{\text{sync}} - \omega_{\text{meas}(D)} \right) \cdot \left( \frac{V_N}{V_{\text{meas}}} \right)^2 = \frac{s_{\text{meas}(D)}}{s_N} \cdot \frac{V_N^2}{V_{\text{meas}}}
\]

(7)

\[
K_{s2} = \frac{s_{\text{meas}(D)}}{s_{\text{meas}(Y)}}
\]

(8)
The indicators $K_{11}$ and $K_{s1}$ are obtained without disconnecting the IM, and the indicators $K_{12}$ and $K_{s2}$ require the IM winding connection change.

For the experimental data set, the indicators $K_{11}$, $K_{12}$, $K_{s1}$ and $K_{s2}$ and its average, standard deviation and variation in function of the load factor, in relation to point $\alpha$, were obtained. The standard deviation ($\sigma$) is given by (9), where $n$ is the number of samples.

$$\sigma = \sqrt{n \sum_{i=1}^{n} x_i^2 - \left(\sum_{i=1}^{n} x_i\right)^2 \over n(n-1)}$$

(9)

The $K_{12}$ average value is 1,67 ($\sigma=0,13$), which is also equal to the ratio between the Y and D power factors in point $\alpha$, as it can be seen in (4).

In relation to point $\alpha$, the D to Y winding connection change leads to a 3-4 times slip increase, as it was demonstrated by $K_{s2}$. The $K_{s1}$ values variation is reduced ($\sigma=0,03$ for an average equal to 0,27). This indicator is more reliable than $K_{s1}$ because the nameplate speed values have significant errors related to the numerical round process (the speed values are rounded to 5 r/min multiples). It can be concluded that if $K_{s2} \geq 0,30$ there is a very high probability (100% of the tested and simulated IMs verify that condition) of IM energy consumption reduction. Note that, for the IMs with a $K_{s2} < 0,30$ in the point $\alpha$, if a $K_{s2} \geq 0,30$ is verified in a real situation, they are operating in the zone where energy consumption reduction can be obtained with D to Y winding connection change.

The indicator $K_{s1}$ includes a voltage correction related to the fact that, for a constant torque, the slip is approximately inversely proportional to the voltage square. If there is a difference between the applied voltage and its nominal voltage, it is necessary to compensate the slip, considering the relation between the two voltages. The indicator $K_{s1}$ is easy to obtain (it is necessary a stroboscopic tachometer and a voltmeter) but has errors related to the speed measurement device errors (typically $\pm 1$ r/min) and to the nameplate speed errors. The $K_{s1}$ values variation is reduced ($\sigma=0,05$ for an average equal to 0,29). It can be concluded that if $K_{s1} \leq 0,25$ there is a high probability (92% of the tested IMs and 100% of the simulated IMs verify that condition) of IM energy consumption reduction. In the simulated data, it can be concluded that $K_{s1}$ slightly increase with the rated power. Note that, for the IMs with a $K_{s1} > 0,25$ in the point $\alpha$, if a $K_{s1} \leq 0,25$ is verified in a real situation, they are operating in the zone where energy consumption reduction can be obtained with D to Y winding connection change.

Although all indicators present low standard deviation, it is important the evaluation of its variation when the load factor is moving away from point $\alpha$. The indicators with higher variation are more appropriate because they have higher immunity to the errors associated to the measurement devices.

The average parameter variation for a load factor equal to point $\alpha \pm 10\%$ is very significant for $K_{12}$, $K_{s1}$ and $K_{s2}$. The $K_{11}$ is not a good indicator because it has a very low variation ($\pm 2\%$), tending to 0% in the IMs with $P_N \leq 1$ kW.
In general, the slip-based indicators are more suitable to field purposes because they have both lower standard deviation and higher average variation in function of load factor. Additionally the measurement of the slip is normally easier and faster than the measurement of the line current.

It can be concluded that $K_{s1}$ allows a preliminary evaluation of the efficiency improvement possibility before disconnecting and changing the winding connections. After changing the connection, $K_{s2}$ can be used to check with more accuracy the savings.

5 Field Evaluation Method

From previous sections, an easy and quick winding connection field evaluation method (Figure 5) can be defined based only on the $K_{s1}$ and $K_{s2}$ indicators.

The possibility of efficiency improvement after D to Y change has to be determined based on the nameplate and measured speed and voltage values without disconnecting the IM, i.e., using $K_{s1}$. As it was demonstrated, the D to Y change should only be made if $K_{s1} \leq 0.3$, with a high possibility of efficiency improvement. After D to Y change a slip based re-evaluation should be made using $K_{s2}$. If $K_{s2} \geq 0.3$ the Y connection should be maintained, otherwise the winding should be D re-connected. Note that, even if there are no significant efficiency improvements due to the proximity between the load factor and the point $\alpha$, the power factor will always significantly improve.

Although the proposed method was only validated for IMs with power between 185 W and 7.5 kW, it can be applied in all IMs, because $K_{s2}$ is independent of the rated power and $K_{s1}$ slightly increase with the rated power. This was demonstrated by the simulation results for the 11 kW and 300 kW IMs.

Figure 5: Winding connection field evaluation method
6 Additional Considerations

The IM speed reduction after D to Y change (Figure 4b) is also important to analyze. The speed reduction is related to the winding voltage reduction and the consequent torque-speed curve shape change (the torque is approximately proportional to the voltage square). This fact can lead to significant power reductions in loads where power is proportional to the speed cube, e.g. centrifugal pumps and fans. However, in the centrifugal pumps case, it is necessary to ensure that the speed reduction does not lead to insufficient flow (the flow is proportional to the speed).

Additionally, after the D to Y change, the speed reduction for different load types has also to be analyzed. In fact, the speed reduction leads to a decrease of the load factor and if the load factor is below point $\alpha$ ($\psi \approx 1/3$), the efficiency improves.

For a speed reduction of $\Delta \omega = (\omega_D - \omega_Y)/\omega_D$ several outcomes are possible depending on the type of the torque characteristics of the load:

- Loads with constant horsepower ($P_{\text{mech}} \approx \text{const.}$), then $\psi_Y = \psi_D$
- Loads with constant torque ($P_{\text{mech}} \propto \omega$), then $\psi_Y = \psi_D (1-\Delta \omega)$
- Loads with linear torque ($P_{\text{mech}} \propto \omega^2$), then $\psi_Y = \psi_D (1-\Delta \omega)^2$
- Loads with quadratic torque ($P_{\text{mech}} \propto \omega^3$), then $\psi_Y = \psi_D (1-\Delta \omega)^3$

Another important consideration is the starting period for high inertia loads and/or loads with demanding torque requirements (e.g. constant horsepower or constant torque loads). In these cases the starting torque reduction to 1/3 of the nominal value can lead to a significant increase of the starting period or even to the lack of starting capabilities. Motor starting in the Y configuration needs to ensure that the motor torque is able to accelerate the motor in a suitable timeframe.

Another potential benefit of the Y connection is that it eliminates the circulating currents possibility associated with unbalanced systems, responsible for additional winding losses, contributing to the IM reliability and efficiency increase.

7 Economic Analysis

The power factor and efficiency increase leads to a reduction in the operating costs. Oversized motors are by far the most important cause of poor power factor in power systems networks. This problem is particularly serious in developing countries, which already face an undercapacity problem, additionally leading to large voltage fluctuations. In practical terms the power factor increase leads to the decrease of kvarh bill and a better exploitation of the electric installations due to the overload, including lower losses. The efficiency has direct impact on the kWh bill. The value of the annual savings, $S$ (€/year), with the D to Y change is given by (10), where $i$ is the operating period with duration $h_i$ (hours/year), constant mechanical power $P'_{\text{mech}}$ (kW) and electrical energy average cost $C_i$ (€/kWh).
In the considered experimental data set, for load factors with a value 10% under point $\alpha$, the average efficiency increase from D to Y change is 2 percentage points. In the same conditions, the power factor average increase is around 0.35. In point $\alpha$ the power factor average increase is 0.34.

Note that, except for constant power loads, after D to Y change, the IM input active electric power decreases due to the motor efficiency increase and due to the speed decrease.

In the presented economical analysis a permanent connection change is assumed, which can be revaluated periodically. For medium-large power motors with a wide load variation and with long low-load periods of duty-cycle, an automatic winding connection change device can be used, but there is a need for an extra modest investment. For this purpose, a low-cost microcontroller based electronic device to switch D/Y contactors in function of the motor current was developed and successfully tested.

8 Conclusions

Motor oversizing is a widespread practice due to a combination of factors associated with the motor market, which is largely dominated by OEMs. With grossly oversized motors there are substantial benefits in terms of efficiency and power factor, operating the motor in the Y connection mode instead of the D connection mode. This paper provides a technique, based on simple measurements, which can be used to select the most appropriate operation mode.

The replacement of an oversized low efficiency or standard motor (EFF 3), by a properly sized high efficiency motor (EFF 1) is, in most cases, an economical advantageous option, but requires additional investment. However, if the user applies the described method to oversized IMs and/or driving high inertia low duty-cycle loads, the active and reactive electrical energy bill can be significantly reduced and the IM reliability increased. The application of an electronic D/Y decision device can be also a good solution, particularly for medium-high power motors.
9 References


Determining Electric Motor Load and Efficiency, United States of America Department of Energy, Fact Sheet, Motor Challenge, 1997


Motor System Audit and Software Tools III
First Results of DEXA – MCP Program: Developing, Integrating and Disseminating “Energy Efficiency Tool Set” in the European Enterprises

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Abstract

This paper presents the DEXA-MCP programme after less than one year from its beginning, and the way it takes to develop the Motor Challenge go to a real European Industrial Challenge for motor’s electrical consumption under general energy efficiency vision.

The DEXA-MCP programme is a SAVE project, supported by the European Commission, that has been launched at the beginning of 2005. Different European contractual partners, 15, and non contractual ones are involved in the project. Its purpose is to disseminate, extend and apply the "Motor Challenge Programme Tool Set": tools created by previous Commission supported projects, in particular the Motor Challenge Programme, EuroDEEM, Life Cycle Costing and the Auditing Programme.

The objectives of the project contain dissemination activities through different ways and much of all with direct contacts, help and guidance to the enterprises. In each European country already involved and which will be involved next in the project, synergies and complementarities are being developed with national energy efficiency policies.

1 The Motor Challenge organization

1.1 The Motor Challenge objectives

The Motor Challenge Programme was launched in 2003 after a 2 years project under the SAVE Programme with the participation of 13 partners\(^1\) such as high energy and technical knowledge centres or institute and national agencies, the Join Research Centre for the European Commission and with the participation of the main concerned European Manufacturer organizations.

The Motor Challenge is based on several studies such as LCC Guidelines project, Compressed Air Systems, pumps, fans, Variable Speed Drives for Electric Motor Systems, studies. All these specific topics led to the following key points:

- 1 – Electric motor driven systems account for 69% of industrial electricity consumption in Europe. The economic and technical potential for savings in Europe is evaluated at more that 100 TWh/year.

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\(^1\) ADEME, CRES, DEA, ADENE, ISR-UC, ENEA, STEM, EVA, IFE, AEA Technology, ARENA, FZJ
• 2 – In order to achieve the potential savings, the systems approach is necessary since a large part of the potential savings are related to system design, installation and maintenance, rather than the performance of individual system components.

• 3 – Energy efficiency programmes in industry encountered a wide number of blocking points which have to be taken into account such as:
  − Motor systems electricity consumption is "invisible" to top management.
  − Electricity consumption is usually treated as a general overhead item in analytical accounting schemes, thus diluting responsibilities for cost reduction.
  − Purchasing procedures rarely take into account long term energy and operating costs.
  − Responsibility for potential optimisation measures is largely diffused among several management functions: Production, Maintenance, Purchasing, Finance.

The Motor Challenge Programme was designed to address these barriers to increase industrial energy efficiency, through an approach and an organization specified below.

The Motor Challenge deals with motor driven systems which ensure the maximum effectiveness of energy efficiency measures. These systems and several actions such as high performance products or well-designed maintenance procedure approaches gives the industry the opportunity to reach some other essential gains like products quality, better global efficiency or longer life time for production tools.

The motor systems covered by the Motor Challenge are:

• Compressed Air Systems
• Ventilation Systems
• Pumping Systems
• Motors and drives

The programme has built for all these systems specific and simple technical guidance in order to give a number of the clues to achieve the energy efficiency gain potential.

### 1.2 The MCP organization

The Motor Challenge Programme aims specifically at industrial use of electricity in Motor Driven Systems. The Motor Challenge Programme is designed to be:

• flexible and open, so as to be applicable to the great variety of user situations;
• sufficiently precise to ensure that companies that participate in the MCP will achieve a significant part of potential energy savings;
• adaptable to the large variety of national programmes and agencies in Europe.

**Motor Challenge is a Label:** between all the possible actions and organizations, such as advertising campaign, technology demonstration, measuring campaign, training and education, life cycle costing approach, economic and regulatory actions, certification
like EMAS or ISO, the labelling companies procedure is the one which assure the respect of a wide part of the previous conditions.

Though, the Motor Challenge label is designed to address these previous barriers to increase industrial energy efficiency, through an approach based on voluntary commitments, defined by each participating enterprise and organization. 2 labels have been created: the “Partner” and the “Endorser” labels.

- Companies that use Motor Driven Systems can request “Partner” status.
- Organizations that wish to assist MCP Partners in achieving the goals of the Motor Challenge may become Motor Challenge "Endorsers".

1.2.1 The partner

The core of the Motor Challenge label is the Action Plan, by which an MCP Partner enterprise commits to undertaking specific measures to reduce energy consumption. These clearly defined and verifiable measures should lead to realising the bulk of profitable energy savings measures in factories of participating companies. The Partner company determines which production sites, and which types of systems, are covered by the commitment. The scope of the commitment is flexible, and can be limited to a single shop, a site or may include all of the company's European production sites. The programme is a voluntary programme, and companies may withdraw from the programme at any time.

An enterprise wishing to join the Challenge programme will proceed by the following 5 step process.

1. Inventory and evaluation of the enterprise's Motor Driven Systems.
2. Formulation of an Action Plan, defining the scope and nature of the enterprise's commitment.
4. Execution of the Action Plan, and annual reports to the Commission.
5. Commission renewal of Partner status, upon review of the annual report.

1.2.2 The Endorser

Any organisation that contributes to the goals of the MCP can become an Endorser. Thus, Endorsers are the "Ambassadors" of the MCP. Endorsers commit to carrying out an MCP Promotion Plan, which can comprise:

- disseminating information on the MCP;
- encouraging user enterprises to become MCP Partners;
• aiding MCP Partners in putting into practice, the recommendations of the relevant MCP Compressed Air, Fan, Pump or Drives "Module" documents.

Manufacturers of Motor Driven System components, engineering consultancies, trade associations, training or educational institutions, electricity companies or ESCOs could become Endorsers.

An enterprise wishing to join the Challenge programme as an endorser will proceed by the following 4 step process.

(1) Formulation of an Promotion Plan
(2) Approval of the Promotion Plan by the Commission (JRC). Commission grants Endorser status to Enterprise.
(3) Execution of the Promotion Plan, and annual reports to the Commission.
(4) Commission renewal of Endorser status, upon review of the annual report.

For each European country participating in the programme, there is a National contact point who is in charge of the animation of the Motor Challenge in his country which means diffusing the motor challenge in the country and being the first direct contact for the enterprises to give help and advice. There are 19 National Contact Points in the following countries:

Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Lithuania, Norway, Poland, Portugal, Slovenia, Spain, Sweden, Switzerland, The Netherlands, United Kingdom.

2 DEXA-MCP: The objectives and the way to first results

DEXA-MCP so as “Dissemination, Extension and Application of the Motor Challenge Programme”, launched at the beginning of year 2005 has been designed to emphasis the Motor Challenge Programme described previously.

The project has a wide range of objectives, but over all it targets to federate the efficiency of several well known European programmes:

- the main objective is to introduce on the long term the MCP into national energy efficiency programmes in order it shall become a recognize tool for energy efficiency politics in all EU countries.
- it proposes to redesign partly the MCP procedures in order to propose a real challenge to the industrial companies

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2 DEXA-MCP participants: ADEME, CRES, ENEA, EVA, DENA, FhF-ISI, senter NOVEM, ADENE, UC-ISR, JSI, LEI, STEM, MOTIVA, AERE, EB
It publicises and complements the Motor Challenge Programme (MCP) in order to complete the analysis of the wall part of electricity consumption in an industrial site under a global energy efficiency policy.

It uses the results of the PROMOT project, which completes the EuroDEEM data base with a whole web tool applications on motor systems.

It disseminates the Life Cycle Costing Guidelines and the set of SAVE studies on drives, VSDs, compressed air, fans and pumps.

In this project, for each European country involved, synergies and complementarities are being developed with national energy efficiency policies, but with a European ambition, coordination, motivation and support.

Participating countries as contracting partners are:

Italy, Greece, France, Austria, Germany, The Netherlands, Portugal, Slovenia, Lithuania, Sweden, Finland.

The project is still open to new collaborations.

The project activities are carried out in close co-ordination with the participating industry trade associations, including the manufacturers associations (PNEUROP, EUROPUMP, EUROVENT, ECI) and associations of energy using industries.

2.1 **DEXA-MCP objectives**

DEXA-MCP is built with specific internal objectives with one goal: creating in the wide Europe real and continue progress in the industry energy efficiency in electricity and motor systems.

The DEXA-MCP project focuses on stimulating with a real challenge for the industry sector, disseminating, extending and applying Motor Challenge Programme through national energy efficiency programmes. These internal objectives are the following:

- **Dissemination of the Motor Challenge and energy efficiency tools**
  A broad ranging programme of publicity, publication, public interventions, are being engaged in each country. Integration of the tool set into national energy agency programmes and practices are the key point to achieve a real efficiency in each country context.

- **Enterprise interventions**
  The DEXA project is built on numbers of direct contacts with Enterprises. These contacts are mainly established through the national energy efficiency programmes such as auditing programmes, help decision tools distribution, financial support, offering advice and information, etc. The aim is to reach a high level of enterprise interventions, carrying out more than 150 enterprise interventions (as compared to the 18 enterprise audits carried out in the MCP pilot project) to ensure a real dynamic of the label and the programme.
Extension of the programme in Europe
New national focal points are brought into the MCP: Finland, Lithuania, Slovenia. The new countries, in particular the accession countries joined the EU in May 2004, will be invited to participate in the programme.

Creating tools
New, simple to apply tools are being creating complimentarily with the existing ones such as ProMot (web based tool on energy efficiency on motor systems) so as to ease their particular application in SMEs, including in situations where no publicly sponsored intervention is carried out.

Technical extension of the Motor Challenge Programme
The Motor Challenge technical environment centred on 4 motor systems (Compressed air, ventilation, pumping, motors and drives) is enlarged to other real important electrical system consumption: Industrial refrigeration and Industrial electricity distribution system. The Motor Challenge modular approach is extended, through the building of two new modules for these important cross cutting energy using technologies.

While these objectives have demonstrated their value individually, they will not achieve their full potential unless they are really and thoroughly integrated into the programmes and practices of the National Energy Agencies and Organisations. With the complementarities of all the tools in a single package offered to the industry, the Motor Challenge Label and recognition is able to stimulate a wide part of the industry through real energy efficiency objectives.

2.2 European Motor Challenge Program: way to first results of DEXA-MCP programme

Motors and motor driven systems efficiency is a part of global energy efficiency and the first ones has to be integrated in the second to give its integral gain and benefit potential to the industry. Within this global approach, Motor’s energy efficiency industrial policy is able to be more and more applied.

The way developed in DEXA-MCP will drive to a real integration in a wide European part of the Motor Challenge label dissemination. The following points are explaining why this way is leading to results.

New European contact points in the Motor Challenge Programme are being coached by countries which are experienced in the project. Communication and dissemination are more efficient because using the past, more efficient because being made together. More other, participation and action in Motor Challenge in new countries are stimulating activities for the older contact points.

Integrating the Motor Challenge into the national programmes leads to a real efficiency by boosting both of the project. Indeed, most of the countries involved in developing the Motor Challenge dissemination have their own energy efficiency programme, and a
wide part of these integrate auditing which is fully complementary with MCP organization. For example, in France, ADEME is helping financing more than 500 audits a year. In the direct continuation of the high level of quality audit defined, obtaining the European label with a National environment for the enterprise is very simple which has something stimulating. The need for this type of co-operation is particularly pressing for the objectives of the MCP. On the one hand, the support for the type of private sector decision makers which the MCP targets, would be most effective at an European wide level, since the advantages offered, in terms of image and public recognition, would be most effective at a transnational level. On the other hand, the bulk of the actual work to identify and carry out technical energy savings measures would have to be done at the local level, through national, regional or municipal energy agencies.

By creating real challenge for electrical and motor energy consumption under the whole consideration of energy efficiency in the industry, with a national and European co-management, with a real experimentation during this DEXA-MCP project, Motor Challenge Label is in a good way to involve several competitive enterprises, supported by specific tools and organizations, for stimulation in energy efficiency ambitious and benefit programmes.

3 References

- “Pilot Action for Motor systems Industrial Use Challenge“:
  - SAVE study 4.1031/Z/00-026/2000

- “Promotion of efficient electric Motor systems“:
  - SAVE study 4.1031/Z/02.048/2002

- “Dissemination, Extension and Application of the Motor Challenge Program” SAVE study EIE/04/164/S07.38650
MCP: The Danish Results

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Abstract

In this paper we will show how Danish companies use the Motor Challenge Programme (MCP). We
will present case studies from a large amount of businesses. We will present company results due
to the use of the different types of guidelines. Also we will try to show how MCP works in
corporation with quality management, environmental management systems and others company
management systems. At last we will present how we promote MCP in Denmark and present our
action plan for the goal of 100 more MCP partners in Denmark.

Case studies

Through a number of cases, we will present result from several Danish companies working with
MCP. We present the difference in working with MCP in small businesses and in larges businesses.
Also presenting new ways of working with MCP. As a part of these studies we will present how the
Danish company York Refrigeration saves 250 MWh by using MCP as basis for a leak check
programme. How Baby Dan A/S optimize ventilations plants by nearly 25% and other very
interesting studies.

MCP and other management systems

Here we will present cases of Danish companies work with MCP as a part of for example
environmental management (ISO 14001 and EMAS). We will present how MCP is integrated in
ISO14001 management systems and works as the action plan for make effective motor driven
systems.

The Danish action plan

The Danish Energy Authorities plan for 100 more MPC partners in Denmark will be presented. We
have a ambitious action plan / promotion plan working with different means. We will also give our
experience with different means. What works, what does not! To get 100 more partners it must be
assumed, that the means works.

1 Case studies

1.1 How York Denmark optimized Air pressure systems and Ventilation Plants through use of Motor Challenge Programme

YORK Denmark is the world’s largest supplier of industrial and marine refrigeration
systems, control systems, equipment, and services. YORK Denmark head office is
located at Holme (Aarhus) where there are 900 employees. YORK Denmark is a divi-
sion of YORK International, a multi-national corporation with over 23.000 employees
and an annual turnover of approx EURO 4 billion.

Electricity is used in the manufacturing processes of the refrigeration systems (welding
machines, CNC, surface treatment etc); add to this ventilation, light and compressed
air. YORK Denmark’s total electricity consumption in the past four years is shown be-
low:
1.1.1 Management Policy - Health, Safety and Environment

In relation to YORK Denmark’s activities the employees’ safety and health have top priority together with environmental considerations. YORK Denmark also takes care not to damage the environment or expose the health and safety of the employees, customers or the public to danger. York Denmark have taken the following initiatives to comply with this policy:

- We obey the law and comply with instructions as to environment, health and safety
- We incorporate environment, health and safety in YORK activities where relevant
- We take the lead to spread policies within environment, health and safety to all employees
- We offer relevant training
- We are working on avoiding work-related injuries and illnesses
- We find ways in which we avoid waste and discharge of contaminants from our activities
- We go through our products and activities on a regular basis to make sure that we comply with the policies
- We constantly improve our efforts related to the environment and the work we perform so that the working conditions are safe and healthy for our employees
• We are all responsible for ensuring the health and safety of our employees and for protecting the environment where we have our activities

• To succeed we must all work together on this, the management, white-collar workers and blue-collar workers.

The company was introduced to the Motor Challenge Programme during the summer 2004 and saw the possibility to use the guidelines in the MCP for a further focus on optimizing systems.

York Refrigeration scoped the following modules:

• Air Pressure Systems
• Ventilation Systems.

1.1.2 Air Pressure Systems

The compressor plant in building no 11 is supplying eight buildings of 34.700 m2 with compressed air through a distribution system. The compressed air is primarily used in small working areas, but some large machines also use the air for eg gripping device.

The plant consists of a main compressor and another compressor for peak loads, totaling 145 KW. Subsequently the air is conducted through a water separator before further distribution. The distribution system was built in 1958 and extended later. The plant was rebuilt in 2001.

The central unit and the compressed-air system have been reviewed as to adjustment, compressor and motor efficiency, pressure drop, leakage and waste heat recovery.

The central compressed-air unit includes two Atlas Copco screw compressors with variable speed. The compressors work on pressure of 7.3 and 7.4 bar. The compressors have a capacity of 25,5 m3/minute. The electricity consumption related to compressed air is about 758 MWh/year or 6% of the total electricity consumption.

The compressed-air system is built of 2½ inches main pipes and ¾ inches coupling pipes from the main pipes to the filling places. The filling places have eg machines and instruments. During this review several possible projects were found. It may eg be possible to partly stop the compressed-air system in weekends. Other possibilities are illustrated on the next page.

Activity Plan for Compressed-Air Module

<table>
<thead>
<tr>
<th></th>
<th>Already implemented</th>
<th>Being implemented</th>
<th>Not considered as evaluation would be unprofitable</th>
<th>To be considered if profitable</th>
</tr>
</thead>
</table>
Tabel 1: The results of the MCP investigations of the air pressure plants.

<table>
<thead>
<tr>
<th>Energy-Saving Goals</th>
<th>Feasibility</th>
<th>Specific Actions</th>
<th>Implemented (in %)</th>
<th>Timing (in months)</th>
<th>Expected savings (MWH/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production of Compressed Air</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Optimized utilization of the system</td>
<td>BC</td>
<td>Partly stop of the compressor in weekends, holidays etc</td>
<td>6</td>
<td>80</td>
<td></td>
</tr>
<tr>
<td>Optimization of compressed-air pressure</td>
<td>AI/BC</td>
<td>Air pressure is as low as possible, but may be further lowered section-wise</td>
<td>6</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>Lower suction temperature</td>
<td>AI</td>
<td>Air taken from outside</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Modify or improve the compressor control</td>
<td>AI</td>
<td>Variable speed used</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Optimization of filter change</td>
<td>BC</td>
<td>Atlas Copco to be consulted</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Filter and dry air for minimum system requirements</td>
<td>AI/BC</td>
<td>Filter quality in relation to requirements. Atlas Copco to be consulted</td>
<td>6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recover and use excess heat</td>
<td>AI</td>
<td>Excess heat is recovered as additional heat for the premises</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Increase main receiver</td>
<td>AI</td>
<td>The 2½ inches distribution pipes function as a large receiver</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Install adjustable machine drives</td>
<td>AI</td>
<td>Atlas Copco to be consulted</td>
<td>6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A multi-pressure system to be considered</td>
<td>BC</td>
<td>Being considered</td>
<td>9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Replace motors by high-efficient motors</td>
<td>AI</td>
<td>Variable motors used</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Replace compressors by new or better adjusted machines</td>
<td>AI</td>
<td>Plant replaced in 2001</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Distribution System</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reduce air leak</td>
<td>BI</td>
<td>On-going</td>
<td>10</td>
<td>3</td>
<td>250</td>
</tr>
<tr>
<td>Divide systems into zones</td>
<td>BC</td>
<td>Being considered</td>
<td>6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Use &quot;air-free&quot; condensed water “traps”</td>
<td>NC</td>
<td>Being considered</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Install supplementary vessels</td>
<td>NC</td>
<td>Being considered</td>
<td>6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Improve the distribution system: Drawings, pipe sizes etc</td>
<td>NC</td>
<td>Not required</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Filling Places</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Elimination of inappropriate use of compressed air</td>
<td>BC</td>
<td>To be investigated internally</td>
<td>12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Repair or replacement of leaking device</td>
<td>BI</td>
<td>Air leak being repaired</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Meet requirements and optimization of device specifications: Pressure control, fillers, dryers</td>
<td>NC</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
In the future, York Denmark will focus on energy efficient design of air pressure plants. When plans are proposed for expansion, York will use the Danish guidelines for efficient design of air pressure plant or by using Best Available Technology.

1.1.3 Ventilation Plants

There are approx 100 ventilation plants on YORK’s 43,000 m². These plants vary from small 1 KW to medium-size air suction ventilators, special plants for paint cabins with advanced air cleaning systems and the comfort ventilation plant of the head office building (8,300 m²). The main part of the plants has been installed/renovated in the past two decades, and a filter change service arrangement has been established.

YORK Denmark's ventilation plants have been reviewed. The purpose of the review was to get a general overview of types, number and the state of maintenance and the age of the machinery.

The capacity of the plants varies from the requirements of a single machine to the requirements of the office building of 8,300 m².

The electricity consumption related to ventilation is estimated to be 1,300 MWH/year or 10% of the total electricity consumption.

The ventilation systems in the production are mainly built of round pipes, and the systems in the office building are mostly built of squareshafts. This is considered the most probable solution out of consideration for the piping through the building and because the piping system is built in 1958 together with the building.

During this review several possible projects were found. It may eg be possible to fully or partly stop more ventilation systems during or after normal working hours and in weekends. Other possibilities are illustrated on the next page.

Activity Plan For Ventilation Module

AI: Already implemented
BI: Being implemented
NC: Not considered as evaluation would be unprofitable
BC: To be considered if profitable
Table 2: The results of the MCP investigations on the ventilation plants.

<table>
<thead>
<tr>
<th>Energy-Saving Goals</th>
<th>Feasibility</th>
<th>Specific Actions</th>
<th>Implemented (in %)</th>
<th>Timing (in months)</th>
<th>Expected savings (MWH/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ventilation Units</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operation schedule</td>
<td>BI</td>
<td>Some units can be stopped when there is no production</td>
<td>10</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>Requirement control</td>
<td>BC</td>
<td>To be investigated further</td>
<td></td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>Selection of the right type of motor and size</td>
<td>BC</td>
<td>To be investigated further</td>
<td></td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>Types of transmission</td>
<td>BC</td>
<td>To be investigated further</td>
<td></td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>Change from V-belt to direct drive</td>
<td>BC</td>
<td>To be investigated further</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Change from V-belt to flat belt drive</td>
<td>BC</td>
<td>To be investigated further</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ventilation piping</td>
<td>BC</td>
<td>To be investigated further</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Selection of ventilator and maintenance</td>
<td>AI</td>
<td>YORK has a maintenance system including the drive systems</td>
<td>50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Variable speed drive</td>
<td>BC</td>
<td>To be investigated further</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Service system</td>
<td>BC</td>
<td>To be investigated further</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fire protection</td>
<td>BC</td>
<td>To be investigated further</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Survey of units</td>
<td>BI</td>
<td>To be investigated further</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Distribution System</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Survey of ventilation</td>
<td>BI</td>
<td>Survey of ventilation equipment</td>
<td>10</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Square pipes</td>
<td>BC</td>
<td>Rearrangement possibilities</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dampers</td>
<td>BC</td>
<td>To be checked</td>
<td></td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>Piping systems</td>
<td>BC</td>
<td>Rearrangement of pressure resistance</td>
<td></td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>Admission /discharge of air</td>
<td>BC</td>
<td>To be checked and reassessed as to pressure drop</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Injection and Exhaust</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air suction at welding working areas</td>
<td>BI</td>
<td>Servicing of dampers and flexible hoses at working areas</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Injection units</td>
<td>BC</td>
<td>To be checked</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Exhaust units</td>
<td>BC</td>
<td>To be checked</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1.2 How Baby Dan A/S in Denmark focus on energy efficiency by using Motor Challenge Programme.

Baby Dan A/S is a manufacturing company producing nursery products as safety equipment, high chairs etc.

Baby Dan is a 100% family owned Danish corporation established in 1947. More than 90% of the products are manufactured in Europe in order to ensure quality and safety. 90% of Baby Dan safety products are manufactured by Baby Dan at their own factories.
The company is residing approx. 35 km west of Aarhus, in the eastern part of Jutland (Denmark).

The company has approximately 100 employees. The electricity consumption is used in the processes for manufacturing the nursery product (welding-machines, CNC, surface treatment etc.), fan systems, lighting and compressed air systems.

### 1.2.1 The use of electricity

The total consumption (electricity) at Baby Dan A/S over the past years is shown below:

![Figure 2: The electricity consumption of Baby Dan A/S 2000 - 2004](image)

### 1.2.2 Air Pressure Systems

The central units and the system for compressed air have been examined regarding to the regulation, compressor- and motor efficiency, pressure level and – loss, leakage and heating recovery.

The central unit for compressed air contain a 52 kW VS (variable speed) 40 – 7.5 EANA Tamrotor compressor working at 6.8 bar pressure level. The compressor has a capacity around 6.5 m³/min. The electricity consumption relating to the compressed air system is about 180 MWh/year or 17% of the total consumption.

The distribution network contains 2½ inch distribution pipes and ¾ inch pipes from the distribution pipe to the end use devices.

The end use contains machines, devices and filter blowing.
There was found a single project during this examination. It was found possible to stop the compressed air system during weekends.

Table 3: Actionplan for further optimizing of air pressure plants.

<table>
<thead>
<tr>
<th>Energy savings measures</th>
<th>Feasibility</th>
<th>Specific actions</th>
<th>% Covered</th>
<th>Time table</th>
<th>Expected savings [MWh/year]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production of compressed air</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Optimise utilisation of system</td>
<td>AI</td>
<td>Turn off the compressor 1 weekends, holidays ect.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Optimise system air pressure</td>
<td>AI</td>
<td>Air pressure is as low as possible</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lower intake temperature</td>
<td>AI</td>
<td>Air is taken from the outside</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Modify or improve compressor control system</td>
<td>AI</td>
<td>Variable Speed is used</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Optimise downstream filter changing</td>
<td>NA</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Filter and dry air to minimum system requirements</td>
<td>AI</td>
<td>Filter quality relates to requirement</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recover and use waste heat</td>
<td>AI</td>
<td>Waste heat is recovered for heating the facilities</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Increase main receiver size</td>
<td>AI</td>
<td>The 2½ inch distribution pipe works as an enormous receiver</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Install adjustable speed drive</td>
<td>AI</td>
<td>Already done</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Consider a multi pressure system</td>
<td>NP</td>
<td>Would require large investments</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Replace motors with high efficiency motors</td>
<td>AI</td>
<td>Variable speed is used</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Replace compressors with newer or better adapted machines</td>
<td>NP</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Distribution network</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reduce air leaks</td>
<td>AI</td>
<td>Air leaks are sequentially sealed</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Divide systems into zones</td>
<td>AI</td>
<td>Already done</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Use &quot;no air loss&quot; condensate traps</td>
<td>NP</td>
<td>Would require large investments</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Install supplemental receivers</td>
<td>NP</td>
<td>The energy saving potential is too low due to the investment</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Energy savings measures

<table>
<thead>
<tr>
<th>Energy savings measures</th>
<th>Feasibility</th>
<th>Specific actions</th>
<th>% Covered</th>
<th>Time table</th>
<th>Expected savings [MWh/year]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Improve network: layout, pipe size</td>
<td>NP</td>
<td>Would require large investments</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>End use devices</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eliminate inappropriate use of compressed air</td>
<td>NP</td>
<td>Not profitable</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Repair or replace leaking devices</td>
<td>AI</td>
<td>Air leaks are sequentially sealed.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Verify need for (and optimise) device specific pressure regulators, filters, dryers</td>
<td>NC</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**AI:** Already implemented  
**NA:** Not applicable for technical reasons  
**NP:** Not profitable  
**NC:** Not considered, because evaluation would be too expensive.

The energy savings through use of MCP has results in approximated savings around 100 MWh (including installation of a variable drive compressor).

## 2 MCP and other management systems

Baby Dan was among the first producers in the nursery industry to gain environmental certification in accordance with the ISO 14001 standard and are still one of the few who are certified.

After being awarded this certification, Baby Dan A/S are obliged to carry out production in such a way as to minimize the possible harm impact of the products to the environment. Baby Dan A/S also make sure that all product waste is disposed of in the most environmentally appropriate way. Among a lot of other aspects, this also means that Baby Dan A/S does not use PVC in any of their products!

Baby Dan will continue to devote their efforts to protect the environment as much possible for the benefit of all of us. Therefore, Baby Dan A/s is also a corporate member of WWF - World Wildlife Foundation.

In order to focus on constant improvement in relation to ISO 14001, Baby Dan uses MCP for input to actions plans for energy saving programmes.
3 The Danish action plan

The Motor Challenge Programme is supported in Denmark by ELFOR (association of Danish Distribution Utilities), The Danish Energy Associates and by the local energy companies.

The goal for Denmark is, that 100 companies join the Motor Challenge Programme before 2010. This year the goal is 10 new partners. To support this The Energy Associates and ELFOR had decided to contact a number of large companies in Denmark. The local energy companies supports this plan by their work on the issue of demand side management.

The plan is to contact companies, who already works with energy efficiency through “voluntary agreements on energy efficiency” with The Danish Energy Associates. Since 1996 Denmark has used voluntary agreements on energy efficiency as an important instrument to improve the energy efficiency in industry. The voluntary agreement scheme is closely integrated with the Green Tax Package as companies, who enter an agreement, receive a rebate on the green taxes. The agreement system has two main objectives. One is to encourage energy-intensive companies to improve their energy efficiency. The other is to ensure that the international competitiveness of energy-intensive companies is retained.

These companies might have the will to work and support the MCP, because the “energy agreements” commits them to do energy saving programmes and because the energy cost might be part of the value chain. An “Energy Agreement” reduces the energy tax payment by doing energy saving programmes. Only heavy users of energy had these possibilities. That kind of agreements are a part of our national energy saving programmes.

The “MCP-plan Denmark” is to:

- Contact the companies by letter and telling them about MCP. About 150 companies have an energy agreement, and only 4 – 5 of these are MCP partners.
- Arrange meetings with potential MCP-partners. ELFOR supports an energy consultant to have meeting with companies to support MCP. The consultant will have in cooperation with the local energy company and the potential partner to verify which MCP modules is relevant using in the potential company. The consultant will verify the energy saving by using the modules as planned.
- Try to integrate MCP in their Value Chain. We find, that the best way to support MPC is to work with energy saving as a part of the companies value chains. This means, that the investments in energy saving programmes have to support other value chains parts as quality, productivities etc.

1 For further information on the Danish Voluntary agreement on energy efficiency please checkout www.ens.dk.
• Support the companies with consultancy helping them mapping the energy and the energy saving potentials.

3.1 Conclusion

From Denmark the following partners has joined MCP:

• Baby Dan A/S
• Contex A/S
• Dalum Paper A/S
• ELMO Leather A/S
• Galvano A/S
• Novozymes
• Scandinavia Brake System A/S
• Valdemar Bin A/S
• York Denmark A/S

9 companies of the 22 partners are Danish, which isolated is very good. All companies have for long time worked with energy efficiency as a natural part of their management. There for, it has been easy to join MCP and to commit them. But for companies, never been familiar til management systems such as quality and environmental, its been “hard work” to prove the value of joining MCP.

In European terms, most of the Danish companies are small. And therefore the energy costs is not in focus compare to heavy energy users. There for, to reach our goal for 100 new MCP partners, we have to think different. The “voluntary agreement”-companies is one opportunity, to integrate MCP I a value chain is another.
Policies and International Issues IV
Energy Conservation through Standards & Labeling of Motors

M. A. Narsimhan, Consultant, International Copper Association, Ltd., Phone: +91 22 25222492, E-Mail m.a.narsimhan@leonardo-energy.org

Hans P. De Keulenaer, European Copper Institute, International Copper Association, Ltd.

Abstract

Background
High Efficiency Motors can contribute significantly to energy savings and help the main objective to reduce energy consumption and GHG emissions.

Many countries have adopted the approach of labeling the equipments consuming large amount of energy. Electric motors, employed to drive various equipments, consume more than 70% of electrical energy.

Standard & Labeling Program (S&L)
This program basically involves categorising and labeling the equipments according to their energy consumption levels. ‘Standards’ are regulations specifying mandatory level of efficiencies for different equipments.

The practices adopted to achieve the objective vary from Country to Country. While many countries including European union, Canada, Korea, China, Mexico and Thailand have voluntary labeling programs for motors, some of the countries including USA, Canada, China, Taiwan, Thailand, Australia, New Zealand have gone in for mandatory MEPS (Minimum Energy Performance Standards)

Standard and Labeling Activities in India
India has problems of severe shortage of power and use of inefficient equipments. Under the Energy conservation Act 2001, the Government has authorized the Bureau of Energy Efficiency (BEE) to take steps to regulate energy usage. Standards and labeling program is one such initiative. Many electrical equipments including Air conditioners, refrigerators, distribution transformers, industrial fans & blowers, pumps, fans and motors have been identified for the program. These equipments contribute a significant portion of electrical energy consumed.

Conclusion
The paper covers the international trends in standards & labeling programs of motors and the proposed steps in India. Motors constituting over 70% of electricity consumption in industries can significantly contribute to energy saving potential, if high efficiency motors are used. Besides the energy saved can help in reducing the demand for additional generation, which requires long gestation period and precious foreign exchange.

BACKGROUND

World over there is increasing concern felt to reduce energy consumption of equipments and protect the environment by reduction of GHG emissions. Governments & organizations are working towards this objective by synchronizing their acts together and forming a long-term approach, which is sustainable. Electricity is one of the basic forms of energy used all over the world, due to its universal availability and ease of use. Electric motors are one of the major users of electricity, employed to drive various equipments in industry, farms, residential & commercial premises. More than 70% of electrical energy produced is consumed by Motors and motor-driven systems. In order to reduce energy consumption, many countries have, adopted the approach of labeling...
the equipments consuming large amount of energy. Motors are one of such equipments due to their high intensity of energy usage.

**STANDARD & LABELING PROGRAM (S&L)**

This program basically involves categorizing the equipments according to their energy consumption levels and labeling them accordingly with star-ratings. For instance, the equipments can be labeled in 5-Star ratings, with single star label indicating highest energy consumption (or lowest energy efficiency) and 5-star label indicating the lower energy consumption (or highest energy efficiency). ‘Standards’ are regulations (also called MEPS) by the Government specifying mandatory level of efficiencies for different equipments. For instance, an equipment having 3 star label may be designated as minimum efficiency level which could be manufactured /sold / used, mandatory in the market.

**OVERVIEW OF S&L FOR MOTORS**

Motors can contribute significantly to energy savings and help the main objective to reduce energy consumption and GHG emissions.

The practices adopted to achieve the objective vary from Country to Country. While many countries including European union, Canada, Korea, China, Mexico and Thailand have voluntary labeling programs for motors, some of the countries including USA, Canada, China, Taiwan, Thailand, Australia, New Zealand have gone in for mandatory MEPS (Minimum Energy performance Standards). The following table gives a summary of the various countries:
<table>
<thead>
<tr>
<th>Economy</th>
<th>Equipment Sub-Type</th>
<th>MEPS</th>
<th>Labeling</th>
<th>National Test STD.</th>
<th>Reference Test STD.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Canada</td>
<td>3-Phase Induction Motors</td>
<td>Ym, Yv</td>
<td>CAN/CSA-C 390-98</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3-Phase Induction Motors</td>
<td>U, U</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>China</td>
<td>1-Phase Induction Motors</td>
<td>Yv</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3-Phase Induction Motors</td>
<td>Ym</td>
<td>GB XXXX</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Malaysia</td>
<td>3-Phase Induction Motors</td>
<td>U, U</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mexico</td>
<td>1-Phase Induction Motors</td>
<td>Ym, Yv</td>
<td>NOM-014-ENER-1997</td>
<td>CAN/CSA C747 IEC 60034-1 IEC 60034-2 IEEE 114-2001 JIS 4203 NEMA MG 1 NEMA MG 11</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3-Phase Induction Motors</td>
<td>Ym, Yv</td>
<td>NOM-016-ENER-2002</td>
<td>CAN/CSA C390 IEC 60034-1 IEC 60034-2 IEEE 112 Method B NEMA MG 1</td>
<td></td>
</tr>
<tr>
<td>New Zealand</td>
<td>3-Phase Induction Motors</td>
<td>Ym</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Philippines</td>
<td>1-Phase Induction Motors</td>
<td>U, U</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Singapore</td>
<td>1-Phase Induction Motors</td>
<td>Yv</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chinese Taipei</td>
<td>3-Phase Induction Motors</td>
<td>Ym</td>
<td>CNS 14490</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thailand</td>
<td>1-Phase Induction Motors</td>
<td>U, Yv</td>
<td>TIS 866-2532 TIS 867-2532</td>
<td>IEC 60034-1 IEC 60034-2 IEEE 112 Method B JIC 4210</td>
<td></td>
</tr>
<tr>
<td>Viet Nam</td>
<td>3-Phase Induction Motors</td>
<td>Ym</td>
<td>TCVN 2280-78</td>
<td></td>
<td></td>
</tr>
<tr>
<td>United Kingdom</td>
<td>3-Phase Induction Motors</td>
<td>U</td>
<td>TCVN 2280-78</td>
<td></td>
<td>EN 60034-2</td>
</tr>
</tbody>
</table>

**Summary Table of Equipment: Motors**

**Yv** = Yes, voluntary; **Ym** = Yes, mandatory; **U** = under consideration; **N** = none
INTERNATIONAL TREND

United States of America

It all began in the United States of America in the 1980’s to 1990’s when state electric utilities started ‘Demand Side Management’ (DSM) programs to save energy. The initiative covered one third of all USA states. The approach was to propagate a voluntary standard for high efficiency motors (HEMs) with financial incentives of 50% or more of the premium of the price of HEMs. The standards and the incentives varied from state to state, due to which the manufacturers faced problems of meeting different standards and increasing costs. Many end users in the active states started using HEMs, which achieved 50% share of the market in those states. However many end users with lightly loaded motors still did not buy HEMs. The US Government stepped in, in the 1990’s and promulgated the ‘Energy Policy Act 1992’ which became effective in October, 1997. The act covered the entire country and involved all stakeholders – motor manufacturers, users, utilities and NEMA. The act specified mandatory efficiency standard and testing method for all motors sold in US from 1 to 200 HP. Authorised Laboratory testing & DOE certification no. were also made compulsory. There were no incentives for the mandatory standard, but motors with higher efficiency levels (super efficiency) were eligible for the same.

The following table gives the minimum nominal efficiency level of AC electric motors:

<table>
<thead>
<tr>
<th>Motor H.P.</th>
<th>No. of Poles</th>
<th>Nominal Full-Load Efficiency - Open Motors</th>
<th>Nominal Full-Load Efficiency - Enclosed Motors</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6</td>
<td>80.0</td>
<td>80.0</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>82.5</td>
<td>82.5</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>-</td>
<td>75.5</td>
</tr>
<tr>
<td>1.5</td>
<td>6</td>
<td>84.0</td>
<td>85.5</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>84.0</td>
<td>84.0</td>
</tr>
<tr>
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<td>2</td>
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<td>82.5</td>
</tr>
<tr>
<td>2</td>
<td>6</td>
<td>85.5</td>
<td>86.5</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>84.0</td>
<td>84.0</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>84.0</td>
<td>84.0</td>
</tr>
<tr>
<td>3</td>
<td>6</td>
<td>86.5</td>
<td>87.5</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>86.5</td>
<td>87.5</td>
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<tr>
<td></td>
<td>2</td>
<td>84.0</td>
<td>85.5</td>
</tr>
<tr>
<td>5</td>
<td>6</td>
<td>87.5</td>
<td>87.5</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>87.5</td>
<td>87.5</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>85.5</td>
<td>87.5</td>
</tr>
<tr>
<td>7.5</td>
<td>6</td>
<td>88.5</td>
<td>89.5</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>88.5</td>
<td>89.5</td>
</tr>
<tr>
<td>Motor H.P.</td>
<td>No. of Poles</td>
<td>Nominal Full-Load Efficiency - Open Motors</td>
<td>Nominal Full-Load Efficiency - Enclosed Motors</td>
</tr>
<tr>
<td>-----------</td>
<td>-------------</td>
<td>------------------------------------------</td>
<td>---------------------------------------------</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>87.5</td>
<td>88.5</td>
</tr>
<tr>
<td>10</td>
<td>6</td>
<td>90.2</td>
<td>89.5</td>
</tr>
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<td></td>
<td>4</td>
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<td>89.5</td>
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<td>4</td>
<td>91.7</td>
<td>92.4</td>
</tr>
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<td></td>
<td>2</td>
<td>91.0</td>
<td>91.0</td>
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<tr>
<td>30</td>
<td>6</td>
<td>92.4</td>
<td>91.7</td>
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<td>40</td>
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<td>4</td>
<td>94.1</td>
<td>94.1</td>
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<tr>
<td></td>
<td>2</td>
<td>93.0</td>
<td>93.0</td>
</tr>
<tr>
<td>100</td>
<td>6</td>
<td>94.1</td>
<td>94.1</td>
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<td>4</td>
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<td>94.5</td>
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<td></td>
<td>2</td>
<td>93.0</td>
<td>93.6</td>
</tr>
<tr>
<td>125</td>
<td>6</td>
<td>94.1</td>
<td>94.1</td>
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<td>94.5</td>
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<td></td>
<td>2</td>
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<td>150</td>
<td>6</td>
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<td>95.0</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>95.0</td>
<td>95.0</td>
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<tr>
<td></td>
<td>2</td>
<td>93.6</td>
<td>94.5</td>
</tr>
<tr>
<td>200</td>
<td>6</td>
<td>94.5</td>
<td>95.0</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>95.0</td>
<td>95.0</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>94.5</td>
<td>95.0</td>
</tr>
</tbody>
</table>
Many industries in the US formed a ‘Consortium for Energy Efficiency’ and defined their own higher efficiency standard called CEE-premium voluntary standard. These standards were typically 1-3% higher than the mandatory EPAct standards (see table below).

<table>
<thead>
<tr>
<th>HP</th>
<th>KW</th>
<th>EPACT</th>
<th>CEE Premium</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.75</td>
<td>82.5</td>
<td>85.5</td>
</tr>
<tr>
<td>5</td>
<td>3.7</td>
<td>87.5</td>
<td>89.5</td>
</tr>
<tr>
<td>10</td>
<td>7.5</td>
<td>89.5</td>
<td>91.7</td>
</tr>
<tr>
<td>25</td>
<td>18.7</td>
<td>92.4</td>
<td>93.6</td>
</tr>
<tr>
<td>50</td>
<td>37.3</td>
<td>93.0</td>
<td>94.5</td>
</tr>
<tr>
<td>100</td>
<td>74.6</td>
<td>94.5</td>
<td>95.4</td>
</tr>
<tr>
<td>200</td>
<td>149.2</td>
<td>95.0</td>
<td>96.2</td>
</tr>
</tbody>
</table>

Electric utilities are developing premium high efficiency motor standards for DSM & rebate programs. Many industries including petrochemical, automobiles are setting their standards higher than the mandatory levels to derive maximum benefits of energy savings and reduce costs.

Utilities, industries, associations & the Government are continuously co-coordinating their activities to define a unified concept for premium efficiency motors.

**European Union**

European union decided to seek a voluntary agreement with the European motor manufacturers represented by CEMEP - the European Association of the individual motor associations of each country. Under the agreement, all motors form 1.1 kW to 90 kW (2 pole / 4 pole) are labeled from 2000 onwards as ‘eff 3’, ‘eff 2’ & ‘eff 1’.

Agreement between CEMEP & European Union:

Further it was agreed that no. of ‘eff 3’ motors sold in Europe would be reduced by 50% by 2003. It is expected that the European union with seek to ban the sale of ‘eff 3’ motors by 2006. The effect of these steps is already producing the desired results. The sale of ‘eff 3’ motors has declined from 68% in 1998 to 44.90% in 2000, while the sale of ‘eff 2’ has increased from 30% in 1998 to 49% in 2000. The sale of ‘eff 1’ motors has also increased from 2% to 6.1%.

**OTHER COUNTRIES**

Many other countries such as Canada, China, Mexico, Australia, New Zealand have gone in for mandatory MEPS and also voluntary labeling for higher efficiency standards.
These steps have been taken from 2000 to 2002 and it will require some time to completely assess their impact.

**Testing Standards**

Any discussion on motor efficiency will remain incomplete without covering the testing standards. While most of the countries in Europe & Asia have adopted IEC 600034-2 standards, countries such as USA, Canada, Mexico etc. have specified IEEE - 112 test method B as the testing standard. The difference lies in the test methods & resulting impact on the efficiency values While IEC assumes a fixed value of stray losses at 0.5% of output, IEEE actually measures the same by tests (stray losses values vary from 0.9% to 1.8% across the range of motors.) Indian standards (IS-325, IS-4029, IS-4884, IS-12615) follow IEC standards.

**STANDARD AND LABELING ACTIVITIES IN INDIA**

India has problems of severe shortage of power and use of inefficient equipments for long. Government rightly recognized the need to conserve energy and promulgated an act called Energy conservation Act 2001, which became effective in 2002. Under the act, the Government has authorized the Bureau of Energy Efficiency in the ministry of power, to take such actions and steps to regulate energy usage in the country. Standards and labeling program is one such initiative in this direction. Many electrical equipments including Air conditioners, Refrigerators, distribution transformers, industrial fans & blowers, pumps, fans, motors have been identified for standards & labeling program. These equipments contribute a significant portion of electrical energy consumed.

As already explained, the equipments are labeled in a 5- star rating scale (or category ‘eff 3’, ‘eff 2’, ‘eff 1’ for motors) and the MEPS will be mandatory specified for each product. The manufacturers and users will be given reasonable period of time to change over to higher levels of efficiency specified under the MEPS. After the time expires, they will be penalized if they use the equipments below the MEPS. To prevent misuse of labels & MEPS, ‘Challenge Tests’ are introduced. These tests can be called for by any one, who is doubtful of the standards offered and if proven correct, the manufacturer will be banned from using the labels. Test protocols, authorized independent test labs are other features of the scheme.

Under the motors standard and labeling programs, which is under finalization by BEE, it is proposed that ‘eff 2’ will be the minimum mandatory efficiency level (MEPS) to qualify for the scheme.
CONCLUSION

The paper attempts to trace the international trends in standards & labeling programs of motors and the proposed steps in India under the EC ACT.

The following graph captures the efficiency levels of America, European Union and proposed Indian MEPS.

It is widely believed that motors constituting 70% of electricity consumption in industries (80-90% in certain industries like textiles, paper & pulp) can significantly contribute to national energy saving potential, if high efficiency motors are used in place of lower efficiency (standard) motors.

The potential in India in various sectors including agriculture is enormous as given below.

The country can save an amount of US $ 3632 million (Indian Rupees 158 billion) per annum approximately, apart from saving of environment due to reduction in GHG emissions. Besides the energy saved can help in reducing the demand for additional generation capacity, which requires long gestation period and precious foreign exchange, apart from related environmental issues due to generation of electricity.
<table>
<thead>
<tr>
<th>Sr. No</th>
<th>User Sector</th>
<th>No. of Motors used (million units)</th>
<th>Motors energy usage (%) (source: CEA)</th>
<th>Estimated Energy Consumption in Million kWh per annum</th>
<th>Energy saving potential due to use of high efficiency motors in place of standard motors in Million kWh per annum</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Industry</td>
<td>20-22 Motor (70)</td>
<td></td>
<td>135,000</td>
<td>13,500</td>
</tr>
<tr>
<td>2</td>
<td>Agriculture</td>
<td>12-13 Pumps (80)/Motors (95)</td>
<td></td>
<td>100,000</td>
<td>20,000</td>
</tr>
<tr>
<td>3</td>
<td>Domestic</td>
<td>45-50 Motors for refrigerators, washing machines, A/C &amp; other appliances (30-40)</td>
<td></td>
<td>60,000</td>
<td>4,000</td>
</tr>
<tr>
<td>4</td>
<td>Commercial &amp; others</td>
<td>1-1.2</td>
<td></td>
<td>40,000</td>
<td>2,000</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>78-86.2</td>
<td></td>
<td>335,000</td>
<td>39,500</td>
</tr>
</tbody>
</table>
Benchmarking of Electric Motor Efficiency Levels in Five Asian Economies

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MSc. Jesper Vauvert, Danish Energy Management A/S, Bangkok, Thailand

Abstract

This paper reports the results of a benchmarking study of electric motor efficiency and performance in five Asian economies. The study examines trade flows, and benchmarks the efficiencies of electric motors produced in Australia, China, India, Malaysia, and Thailand. It was funded by the Australian Greenhouse Office as part of its ongoing effort to benchmark international energy performance levels and to link Australian policy to best international regulatory practice.

The primary goal of the research is to provide a better understanding of the relative efficiencies of those motors in the respective markets, as well as a clearer picture of the origin and destination of motors manufactured in the economies concerned. Analysis of the trade flows show the volumes of motors being exported and imported between the five economies, and thus provide indications as to the effectiveness of regional harmonization of S&L requirements for electric motors. Furthermore the study benchmarks and compares motor efficiency levels in relation to efficiency regulations in place, as well as the relative standing of each economy’s domestic markets, including e.g. market structures, motor efficiencies and prevalence of high efficiency motors.

Of the five economies, Australia has the highest average motor efficiency over the range of motor sizes analyzed. Thailand and Malaysia have comparable market characteristics as regards efficiency, slightly lower than those of Australia. India and China have lower average efficiency levels overall.

The main importance of this new regional benchmarking study of electric motor efficiencies lies in its potential impact on the ongoing national and regional standards and labeling efforts.

1 Introduction

Background

Since the mid- to late 1990s, an increasing number of international meetings on energy policy have found that energy-efficiency standards and labeling programs can deliver cost effective environmental benefits and conserve energy, while also calling for the acceleration and expansion of such programs. However, even though appliances and equipment are internationally traded, policymakers rarely look at international benchmarks when developing thresholds for minimum energy performance standards (MEPS) and labeling. For example, it is extremely rare to find direct, cross-economy comparisons of MEPS and labeling tiers.

The Australian government is beginning to take the lead in the area of benchmarking, in line with the government’s stated policy of examining “international best regulatory practice” when develop new MEPS and labeling requirements. The Australian approach is that its MEPS levels should not be lower than any other economy – or stated
another way, if a product is made in Australia, it should meet the energy and environmental criteria and be able to be sold in any market in the world. The Australian Greenhouse Office’s (AGO) interest in benchmarking energy performance of appliances and equipment is a direct outgrowth of its focus on “best regulatory practice.”

To support its policy of best regulatory practice, AGO has commissioned two international benchmarking studies: one, published in 2004, covered air conditioners; another, the topic of this paper, covers electric motors.

Objectives

The primary objectives of this study are:

1. To benchmark motor efficiencies in these five markets against each other
2. To assess and analyze trade flows between Australia, China, India, Malaysia, and Thailand

Project team

Danish Energy Management (DEM) assembled a team of local consultants in the five economies. The subcontracted national consultants were responsible for collecting and gathering available data in their economy and supplying it to DEM. The data collected referred to trade flow, market structure and motor efficiencies as well as laboratory test data to the extent available.

DEM carried out analyses and cross-economy integration of the data, as well as coordinating the effort, drawing conclusions and writing the final report. Table 1 below gives an overview of the research team.

Table 1: Overview of the study team

<table>
<thead>
<tr>
<th>Economy</th>
<th>Role</th>
<th>Consultant</th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td>Overall coordination and analysis</td>
<td>Danish Energy Management A/S</td>
</tr>
<tr>
<td>Australia</td>
<td>Market and trade data collection</td>
<td>Energy Consult Pty.</td>
</tr>
<tr>
<td>China</td>
<td>Market and trade data collection</td>
<td>China Certification Center for Energy Conservation Products (CECP)</td>
</tr>
<tr>
<td>India</td>
<td>Market and trade data collection</td>
<td>IIEC India</td>
</tr>
<tr>
<td>Thailand</td>
<td>Market and trade data collection</td>
<td>Saangsan Consultants Co., Ltd.</td>
</tr>
</tbody>
</table>
2  Collected data

Overview of the Data

An overview of what data has been collected is given in Table 2. Table 3 provides details of the data collected, based on type of motor unit, number of brands, and number of models for each economy.

Table 2: Overview of Data Collected.

<table>
<thead>
<tr>
<th></th>
<th>Australia</th>
<th>India</th>
<th>China</th>
<th>Thailand</th>
<th>Malaysia</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Catalogue data</td>
<td>Y(\text{\textsuperscript{b}})</td>
<td>Y(\text{\textsuperscript{c}})</td>
<td>Y(\text{\textsuperscript{c}})</td>
<td>Y</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>Test data</td>
<td>Y</td>
<td>N(\text{\textsuperscript{a}})</td>
<td>Y(\text{\textsuperscript{c}})</td>
<td>N(\text{\textsuperscript{a}})</td>
<td>N(\text{\textsuperscript{a}})</td>
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<tr>
<td>Trade data</td>
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<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Market data</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
</tbody>
</table>

Notes: a) For Thailand, Malaysia and India, test data were not available. b) Since in Australia MEPS are enforced, the MEPS registration dataset that have been used contains all models on the market. c) In China and India only relatively small samples were collected.

Table 3: Overview of Data Collected on Motor Brands and Models

<table>
<thead>
<tr>
<th></th>
<th>Australia</th>
<th>India</th>
<th>China</th>
<th>Thailand</th>
<th>Malaysia</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DATA ON MOTOR BRANDS</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Catalogue data</td>
<td>NA(\text{\textsuperscript{1}})</td>
<td>4</td>
<td>5</td>
<td>14</td>
<td>11</td>
<td>NA</td>
</tr>
<tr>
<td>Test data</td>
<td>35</td>
<td>NA(\text{\textsuperscript{2}})</td>
<td>9</td>
<td>NA(\text{\textsuperscript{2}})</td>
<td>NA(\text{\textsuperscript{2}})</td>
<td>NA</td>
</tr>
<tr>
<td>Total number of motor brands</td>
<td>35</td>
<td>4</td>
<td>14</td>
<td>14</td>
<td>11</td>
<td>NA</td>
</tr>
<tr>
<td><strong>DATA ON MOTOR MODELS(\text{\textsuperscript{3}})</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Catalogue data</td>
<td>NA(\text{\textsuperscript{1}})</td>
<td>232</td>
<td>78</td>
<td>789</td>
<td>519</td>
<td>NA(\text{\textsuperscript{4}})</td>
</tr>
<tr>
<td>Test data</td>
<td>2,995</td>
<td>NA(\text{\textsuperscript{2}})</td>
<td>150</td>
<td>NA(\text{\textsuperscript{2}})</td>
<td>NA(\text{\textsuperscript{2}})</td>
<td>NA(\text{\textsuperscript{4}})</td>
</tr>
<tr>
<td>Total number of models</td>
<td>2,995(\text{\textsuperscript{3}})</td>
<td>232(\text{\textsuperscript{3}})</td>
<td>228(\text{\textsuperscript{3}})</td>
<td>789(\text{\textsuperscript{3}})</td>
<td>519(\text{\textsuperscript{3}})</td>
<td>NA(\text{\textsuperscript{4}})</td>
</tr>
</tbody>
</table>

Notes: NA = not applicable. 1) Model data was sourced directly from the MEPS registration database. Therefore catalogue data as such were not collected. 2) For Thailand, Malaysia and India, test data were not available. 3) Covers 2,4,6 and 8 pole motors for Australia, and 2, 4, and 6 pole motors in Thailand, Malaysia, India and China. 4) The model numbers do not match in the different economies. It is therefore not possible to determine the total number of different models in the dataset across all economies.

In order to compare information across the five economies, a number of adjustments to the raw data have been required. In the present paper motor performance data generally refer to IEEE 112 B, whereas collected data – depending on the manufacturer and economy of origin – are refer to variety of standards. The two main reference standards encountered are the IEC 60034-2A and the IEEE 112B. To compare all the data on an
equal footing, conversions of the performance data has been made, so that e.g. values quoted according to IEC 60034-2A has been converted to an equivalent figure within the IEEE 112 B frame of reference.

It was also necessary to adjust some of the trade data provided. This is due in part to the fact that some of the data were provided only in monetary value; and partly due to the fact that data reported by the different economies were inconsistent.

3 MEPS, labeling and testing

Overview of MEPS, Labeling and Testing

Of the five economies surveyed Australia and China have had MEPS in effect from 2001, whereas Thailand, Malaysia and India do not have MEPS. Australia will implement new, more stringent MEPS by 2006, and China is considering increasing its MEPS levels as well. Thailand and India are considering MEPS but the final decisions are still pending. Malaysia has just introduced a voluntary labeling scheme for three-phase electric motors based on the European EFF scheme (identical in terms of efficiency levels), while considerations for MEPS are still undecided. Figure 1 shows current and planned MEPS levels in the five economies.

Figure 1: Current and proposed MEPS levels in the Five Economies
The MEPS stringency level will be raised in Australia in 2006 (2001: light blue, 2006: dark blue). The Chinese MEPS (yellow diamonds) are equivalent to the Australian 2001 MEPS. The proposed Thai MEPS are shown as a dotted red line. The Malaysian (voluntary) EFF 2 and 1 levels are identical to the Australian 2001 and 2006 MEPS respectively.
A comprehensive review of MEPS in APEC economies was conducted for the APEC Energy Standards Information System (APEC ESIS) (Cogan 2003). This study discusses various factors that can influence the comparison of MEPS (and motor efficiencies) when the performance has been determined using different standards.

More comprehensive descriptions covering the five economies can be found in the report upon which this paper is based.

4 Main findings

4.1 Motor Market Characterizations and Trade Flow Analysis

Market Characterizations

The absolute size of the markets in the five economies varies significantly, with China being the largest and Malaysia the smallest national market for electric motors. Table 4 below gives an overview of the sales volumes involved.

Table 4: Motor Sales in the five economies

<table>
<thead>
<tr>
<th>Market Size</th>
<th>US$</th>
<th>Number of units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Australia</td>
<td>49,081,161</td>
<td>310,442</td>
</tr>
<tr>
<td>Thailand</td>
<td>91,245,000</td>
<td>792,374</td>
</tr>
<tr>
<td>Malaysia</td>
<td>--</td>
<td>64,030</td>
</tr>
<tr>
<td>China</td>
<td>3,061,883,565</td>
<td>--</td>
</tr>
<tr>
<td>India</td>
<td>--</td>
<td>993,600</td>
</tr>
</tbody>
</table>

Price relationships that have been derived on the basis of the model data collected show some interesting variations between the economies. It should be noted that for Australia, the price relationship was derived on the basis of secondary rather than from primary data, but the average prices gathered by the local consultant for the present study correspond well with the secondary data used (AGO 2003). The data collected in China only allows a direct relationship to be determined between price and rated power.

The variation, from model to model, in Figure 3 is generally quite high, which testifies to the fact that the price is a function of many parameters apart from the size of the motor. As might have been expected the Australian average price seems to be higher than in the other economies; the Thai and Malaysian average prices are roughly comparable, whereas the Chinese prices appear to be significantly lower than in the other economies. This may to a certain degree reflect the lower average efficiency found for the Chinese market (cf. below), but perhaps also the fact that most motors sold in China use more or less the same basic design.
Figure 2: Accumulated Market Shares as a Function of Rated Power
The full blue curve represents Australia, the dotted blue line an earlier survey done in Australia (AGO 2003); the Red curves represent Thailand (full line — present study’s data; dotted line: ERM Siam 1999); The two green curves for Malaysia similarly represent the present study’s data and an earlier survey (PTM 2002). The yellow line represents China.

Figure 3: Prices as Function of Rated Power (US $/kW plotted against kW)
The blue line represents Australia, the Red China, the green Malaysia and the yellow Thailand.
4.2 Trade Flow Analysis

The purpose of the trade flow analysis was to assess the volume of trade (export, import and net trade), the direction of net trade, and the kind of motors traded between the five economies. The collected information presented in the market overviews gives rise to a number of questions when compared to each other. First, one would expect that the export from one economy to another equals the import into the second economy from the first. However, in taking a closer look at the data this turns out not to be the case, meaning that there are discrepancies in the official data sourced. In most cases the net direction of trade coincides, whereas the volume of trade differs (but is of the same order of magnitude). In some instances, however, neither the volume of trade nor the order of magnitude matches up.

It is also necessary to note that the import/export data from China as presented in the economy overview prepared by the local consultant appear to be a factor 1000 too large (three orders of magnitude larger figures from China than from any of the other economies concerned). Therefore, until further details are available the analysis has assumed that the Chinese figures by mistake have been made a factor 1000 too large.

The overall result of the trade flow analysis is presented in Table 5 below.

Table 5: Net Average trade within the Five-Economy Group (Number of units)
Figures >0 denote net export, and < 0 net import

<table>
<thead>
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<th>To</th>
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</table>

The net direction of trade as well as whether a economy is a net importer or exporter is visualized in Figure 4 below.

Generally speaking, the results of the trade data analysis are quite uncertain as a result of the fact that both the trade figures and the figures for local production and market size are subject to significant uncertainties. The possibility that re-export could be significant in some economies contribute to the understanding of the observed discrepancies, although it is not likely to be the full explanation.
4.3 Motor Model Efficiencies

Based on the collected data model-weighted average efficiency curves have been determined for each economy’s markets. Although it has not been possible to calculate a sales-weighted average due to inaccessibility of model specific sales values, it is reasonable to expect that the sales weighted average efficiency is close to the model-weighted average.

Model-weighted average efficiency curves for each economy are shown in Figure 5, and as can be fairly easily seen there is a distinctly higher average efficiency in the Australian compared to the Thai, Malaysian, Indian and Chinese markets.

The difference in model efficiencies is perhaps most clearly demonstrated (Figure 6) by the percentage of currently marketed motors in each market that would comply (at least in theory) with the more strict MEPS levels that will be introduced in Australia in 2006. Roughly half the current models in the Australian market would be in compliance, whereas the percentages for Thailand and Malaysia are 22% and 25% respectively. A mere 15% of the motors on the Chinese market, and roughly 8% in India would pass these more stringent MEPS. The result for China and India are less certain than the Australian, Thai and Malaysian as a result of the relatively smaller samples.
Figure 5: Model-Weighted Average Market Efficiency Curves
The blue curve representing Australia is distinctly above the Thailand (red) and Malaysia (green) curves. The Chinese and Indian average model averages (yellow and pale blue) are distinctly lowest over most of the range. Note that for the sake of clarity the x-axis is logarithmic.

Figure 6: Percentage of current models that – according to the samples collected - would pass the more stringent, Australian MEPS to be introduced in 2006.
Interestingly the graph in Figure 6 is the same as the percent of models in the samples that are EFF 1, since the AU 2006 MEPS is equivalent to EFF 1. Furthermore all the local consultants' reports state that the % of sales that are EFF 1 is quite low, much lower in fact than the % calculated based on our samples.

5 Conclusions

Data Collected. The study team carried out market surveys and characterized the three-phase electric motor market in each of the economies. Teams also reviewed manufacturers’ catalogues of models available on the market; and collected available laboratory test data on motor performance. The data collection and analysis focused on motors with up to 100kW rated power. A massive amount of data was collected – ranging from 11 to 35 brands per economy; and from 228 up to 2,995 models per economy.

Test Procedures. All five economies have significant numbers of models on their markets using either IEC 60034-2 and IEEE 112-B for measuring energy performance. To compare efficiencies in the different markets the team used a correction algorithm based on the Australian/New Zealand MEPS standard, which include tabulated values of comparable performance figures quoted in accordance with both standards. This allows a direct, albeit not exact, conversion method between performance data.

Catalogue Data Used. Because not all of the economies have comprehensive test data on models available in the market, the team decided to do the primary motor comparisons between the five economies using catalogue data. While there are some potential drawbacks to this approach, the catalogue data is the only common denominator of the available data in each of the economies and thus the only way to ensure that we were comparing “apples with apples.” The exception to this argument is the Chinese catalogues, which apparently does not in general list motor efficiency data. Therefore the Chinese efficiency data are mostly test data.

Efficiency Comparisons. Of the five economies, Australia has the highest average motor efficiency over the range of motor sizes analyzed. Thailand and Malaysia have comparable market characteristics as regards efficiency, slightly lower than those of Australia. India and China have lower average efficiency levels overall.

Other Comparisons. The main report presents a number of representative findings from the large dataset. This includes trade flow data and comparisons of MEPS standards and of the relative energy consumption contributed by different size motors in the market.

The Australian Benchmarking Initiative. This is second in a series of international benchmarking efforts of its kind for appliance and equipment energy efficiency. A similar benchmarking study was carried out for air conditioners and presented at an international conference in Sydney during June 2004. The results of these benchmarking studies will be used by Australia in implementing its policy of “international regulatory best practice” in the establishment of minimum energy performance standards (MEPS)
and labeling grades for its energy labels. They also form the core of a new section on “performance benchmarking” that will be established on the web site of the APEC Energy Standards Information System (www.apec-esis.org) in order to promote international best practice in appliance and equipment efficiency.

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GENERAL BACKGROUND


Leveraging CDM Finance to Promote Efficient Industrial Motor Systems

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Abstract

The Kyoto Protocol entered into force for 140 countries and the EU on 16 February 2005. The Protocol’s Clean Development Mechanism (CDM) is designed to encourage the financing of climate protection projects with local sustainable development benefits in developing countries. We report on several projects designed to leverage additional CDM financial flows to promote efficient industrial motor systems in developing countries. With reference to case studies, we will discuss the potential for the CDM to remove barriers to efficient motor system investments, thus contributing to market transformation and more rapid diffusion of advanced technologies in the developing world. We will present an overview of current efforts to develop credible baseline and monitoring methodologies under such models, discuss specific project examples and assess prospects for the viability of such industrial motor system projects under the Clean Development Mechanism.

1 Motor system efficiency in the climate policy context

Greater diffusion of efficient industrial motor systems will reduce energy use and greenhouse gas emissions rapidly and significantly, while at the same time reducing local air pollution and associated health impacts and easing pressure to install additional fossil fuel electricity generation capacity. The energy efficiency path is of high priority in coal-powered countries with high growth rates like China. Due to pervasive barriers, however, efficient motor systems are not in widespread use. The UN Kyoto Protocol offers new incentives to facilitate efforts to promote efficient motor systems.

1.1 Significance of motor system improvements

In many developing countries, the industrial sector consumes a large fraction of total electricity, and both China and India – which are the largest developing country emitters of greenhouse gases on an absolute basis – rely heavily on coal for their electricity generation. Furthermore, by several estimates, the major electricity use in industry is electrical motor systems in all sizes (from 0.5 to 500 kW m) and in all typical functions (Nipkow and Brunner 2005):

- Pumps for hydraulic systems (water, heating, hot water, sewage, etc.)
- Fans for air systems (air conditioning and ventilation, cooling, heating, etc.)
- Compressors for compressed air
Compressors for cooling systems, heat-pumps,
Traction for elevators, transport belts, etc.

Existing motors systems often tend to have low peak and partial load efficiency, are
over-sized, operated continuously without controls for load management, and use
inefficient components (transformers, gears, coupling, throttles, etc.) and ill-designed
mechanical functions (air ducts, water pipes, elevators, etc.) that decrease overall
system performance considerably.

Because industrial motor systems are pervasive and a major source of electricity
demand, offer great potential for efficiency improvement in new systems and can be
upgraded with short payback periods, they are an important technology focus for
climate mitigation efforts and application of the project-based Kyoto mechanisms,
which are described below.

1.2 Promotion of efficient motor systems under the Kyoto Protocol

The Kyoto Protocol entered into force for 140 countries and the EU on 16 February
2005 (and has since been ratified by 150 Parties). The Protocol contains legally binding
emissions targets for industrialized countries listed in Annex I of the agreement; these
so-called “Annex I countries” are to reduce their collective emissions of six key
greenhouse gases by at least 5% on average over the period 2008 – 2012, compared
with 1990 levels.

One of the novel features of the Kyoto regime is the inclusion of three so-called “Kyoto
mechanisms”, which give countries some flexibility in where, when and how they
achieve the necessary greenhouse gas emission reductions. International emission
trading allows developed countries to buy and sell emission allowances among
themselves. The project-based mechanisms – joint implementation and the Clean
Development Mechanism – make it possible for developed countries to acquire
fungible credits for greenhouse gas emission reductions that result from the
implementation of climate protection projects in other Annex I or in non-Annex I
countries, respectively, to which they contribute financially.

In our paper, we explore how these new climate policy instruments can be used to
facilitate programs to promote efficient industrial motor systems

1.2.1 Kyoto mechanisms: Spotlight on the Clean Development
Mechanism

The focus of this paper is on the Protocol's Clean Development Mechanism (CDM),
which has a twofold purpose, namely to assist:

- developing country (non-Annex I) parties in achieving sustainable development and
  contributing to the ultimate objective of the Convention; and
developed country (Annex I) parties in achieving compliance with their emission limitation and reduction commitments under the Protocol.

Under the CDM, projects that result in real, measurable and long-term climate mitigation benefits (either reduced emissions of greenhouse gases or enhanced uptake/removal of carbon dioxide from the atmosphere), and which are additional to any emission reductions that would otherwise occur, can be validated as CDM projects.

The project has to prove its additionality versus an assumed "business-as-usual" development that is defined as a baseline. The methodologies used to define the baseline, as well as to monitor the actual emission reductions achieved by the project versus the baseline, must be approved by the CDM Executive Board before a project can be registered under the CDM and generate CERs. The actual emission reductions achieved by CDM projects are independently verified ex post and result in the issuance of certified emission reduction (CER) credits.

These credits can be acquired by private and/or public entities and can be used to meet the Kyoto Protocol obligations of developed countries. Each CER represents a reduction or sink enhancement equal to 1 ton of CO2-equivalent emissions. Comprehensive information on CDM institutions, rules and procedures is available from the web site of the UN Framework Convention on Climate Change (http://cdm.unfccc.int/).

1.2.2 Leveraging CDM finance for industrial motor system improvement

Energy efficiency projects are prime candidates for the CDM, because of their large greenhouse gas emission reduction potential, cost-effectiveness of greenhouse gas mitigation and wide range of typical sustainable development benefits (e.g., local pollution reduction, improved reliability of energy supply, reduced demand for fuel imports, job creation, cost savings compared with supply expansion, driver for technology innovation). However, they are poorly represented in the existing pipeline of CDM projects for a number of reasons, in particular, a lack of approved baseline and monitoring methodologies that are cost-effective for large numbers of small projects. In contrast, fuel switching or the use of renewables in power generation systems are relatively straightforward. The same holds true for single large end-use energy efficiency improvements (e.g., a local water pumping system). It is much more challenging to define and get approval for baseline and monitoring methodologies for a dispersed energy efficiency activity, such as the promotion of efficient industrial motor systems throughout an entire country. In this case, a more limited definition of the scope of a DSM project could be necessary to improve its coherence:

a) All motors in use at one large industrial facility;
b) All motors installed by an individual motor producer;
c) All standard-size pumps of a limited number of producers.

An important recent development was the submission in February 2005 of baseline and monitoring methodologies for the Electric Motor Replacement Program in Mexico (which is presented as a Case Study in the next section). This is the first industrial mo-
tor system project submitted under the CDM. Although the CDM Executive Board’s Methodology Panel rejected the proposed methodologies at its 16th session in June 2005, its detailed justification will be of great value in preparing future industrial motor projects under the CDM.

2 Case Studies of industrial motor programs under the CDM

2.1 Mexico Motor Replacement Program
(Source: MGM International 2005, unless otherwise indicated)

Electric motors represent 45% of the national electricity consumption in Mexico (36% in industry, 5% in agriculture, 3% in residential sector, and 1% in municipal services). The proposed program for the entire country of Mexico (population 103 million) is intended primarily for three-phase induction motors among users in industry, agriculture and municipal services.

The purpose of the project is to offer financial incentives to users of electric motors so that they replace inefficient motors in use with new, high-efficiency motors that meet the standards of the FIDE seal (“Sello FIDE”). While voluntary and mandatory standards have improved the efficiency of new electric motors sold in Mexico since 1994, these standards have had little effect on motors that are in use and functional. Electric motors have very long life, and even when they face problems, users may rewind or otherwise repair them (which can reduce their efficiency even further) and continue their use.

The project sponsor, FIDE (“Fideicomiso para el Ahorro de Energía Eléctrica”), is an Energy Savings Trust that promotes electricity efficiency in Mexico, with revenues from various sources. However, revenues from CER sales are the only source of funding available to FIDE to provide the incentives under the motor replacement program, which will be the first of its kind in the country. As a result, it is unclear at present whether the project will go forward, given the Meth Panel rejection of the proposed new methodologies in June 2005.

Key CDM parameters of the project are as follows:

- Baseline methodology: The proposed new methodology draws from two approved methodologies and is based on the case where the baseline is defined in terms of “existing actual or historical emissions, as applicable”, as defined in paragraph 48 (a) of the CDM Modalities and Procedures. This approach is deemed most applicable, because the project involves replacement of a full range of electric motors currently in service, which reflects the nature of demand-side management programs and best practice for evaluating energy savings and greenhouse gas emission reductions. Approaches 48b and c are not applicable, because there is no single technology that can be used as a reference (48b) and no motor replacement program
has been conducted in the past and could not be implemented without CDM revenues (48c). For equipment with a fixed power input, total electricity purchase is given by the product of equipment quantity, power input and the number of operating hours per year. The decrease in electricity use resulting from equipment replacement due to the CDM project can be converted into units of CO₂ equivalent using an emission factor. Transmission & distribution losses within each grid are taken into account.

- **Additionality:** By applying the "consolidated tool for the demonstration and assessment of additionality", investment analysis demonstrates that the value of CDM certified emission reductions (CERs) allows the project sponsor (JPower) to overcome a clear investment barrier (without the value of the CERs, the sponsor would have no incentive to provide resources for the program). Barrier analysis is based on the fact that inefficient electric motors remain in use, despite minimum efficiency standards for new motors in operation for a decade. The barriers are likely to be a combination of investment barriers (e.g., required return on investment levels for energy investments) and those due to prevailing practice (e.g., practice of rewinding old motors, rather than replacing them).

- **Greenhouse gas emission reductions:** As a result of the CDM project, motor energy consumption will be reduced at the users' premises, transmission and distribution losses will be lower and electricity generation at power plants will be reduced, which lowers both fossil fuel consumption and related carbon dioxide emissions. The emissions reductions are estimated to be 0.6 million tonnes CO₂e over the first 7-year crediting period and 2.6 million tonnes CO₂e over the entire 21-year crediting period.

### 2.2 Jiangsu Efficiency Power Plant Project

(Source: Arquit Niederberger and Finamore 2005, unless otherwise indicated)

The Jiangsu project is being developed by the Jiangsu Provincial Economic & Trade Commission and the Natural Resources Defense Council, a US-based environmental organization. It is a multi-sectoral demand-side management program, which foresees the promotion of efficient industrial motor systems as one element in a package of energy efficiency programs. Taken together, these programs conceptually represent construction of an "efficiency power plant" (an EPP is a set of efficiency programs designed to deliver reductions in energy demand that represent the energy and capacity equivalent of a large conventional power plant). Preliminary analysis of the Jiangsu EPP (Asian Development Bank, 2005a) indicates that two years of such DSM investments can lead to a peak demand reduction equivalent to a 464 MW power plant.

Electric motor systems are responsible for over 60% of total electricity load in China and 70% of industrial load (Optimal Energy and State Grid Corporation DSM Instruction Center 2005). In Jiangsu Province (population 74 million), industrial motor systems are the single largest opportunity for energy savings. The planned industrial motor program is therefore a key element of the EPP that addresses all drive power systems in both
existing and new industrial process facilities, including pumps, fans and compressed air systems. The program (Optimal Energy and State Grid Corporation DSM Instruction Center 2005) will rely on ESCOs as the primary marketing and delivery mechanism for:

- cash incentives and/or other financial strategies to reduce the first cost and improve the cash flow related to drive power efficiency improvements;
- technical analysis and assistance;
- education and training;
- information to customers and market actors on relevant policies (e.g. national labelling, certification, efficiency codes and equipment standards, etc.) that will help foster long term market transformation.

Even though investments in energy saving programs under the EPP can provide energy services at a quarter of the cost of constructing new power plants, they still require up-front capital investment. And, in contrast to the well-established practice of financing conventional power plants, lenders lack experience with such diversified programs and are reluctant to provide loans. In addition, tariff structures currently do not allow utilities to charge customers for energy services provided as a result of investments in increased efficiency. To overcome some of these barriers, the parties involved in the Jiangsu EPP are considering developing the proposed EPP under the CDM. The following Figure shows the capital investment cost in 2005-06 and the estimated value of the corresponding volume of CERs for the Jiangsu Province EPP (464 MW), with values given in 2005 present value, discounted at a rate of 6.4% (see Arquit Niederberger and Finamore 2005 for details). At this stage of project development, these estimates are still rough, as they are based on preliminary designs of DSM programs and the resulting rough estimates of abatement costs, energy savings and GHG emission reductions.

Figure 1: Jiangsu Province EPP Utility Cost & CER Value, discounted (Arquit Niederberger and Finamore 2005)
The resulting cumulative GHG emission reductions for the 2007-12 period are 6.3 million tons of CO₂, whereas total emission reductions for the two years of investment are much larger (15.5 Mt CO₂), as they continue over the average 13-year lifetime of the energy saving equipment installed. The Figure therefore shows the present value of CERs generated through 2012 (assuming revenues of RMB 40 / ton CO₂), as well as for the entire crediting period (assumed to be 13 years, for reductions implemented in 2006 and 2007).

3 Overcoming obstacles to motor promotion projects under the CDM

Leveraging additional CDM financial resources from foreign sources is fully compatible with the two motor system efficiency programs outlined above, and would have a number of advantages, including:

- providing a significant additional source of revenues from CER sales (or investment in CDM projects);
- contributing a secure hard currency revenue stream for debt servicing purposes (beginning with the second year of CER transactions, annual CER sales will amount to nearly RMB 48 million for the Jiangsu EPP, which could easily cover loan repayment needs);
- reducing or eliminating possible rate impacts from utility-funded DSM measures;
- improving access to the most advanced technologies available;
- ensuring full value for the Chinese contribution to global climate protection.

However, project developers are faced with a number of challenges to obtain CDM approval. A major hurdle is that new baseline and monitoring methodologies will need to be developed. Given the rejection of the proposed methodologies for the Mexico Motor Replacement Program (a relatively simple motor replacement scheme), deriving credible, cost-effective approaches for comprehensive motor system efficiency improvements promises to be quite challenging.

The “motor community” can promote the uptake of such projects under the CDM in a number of ways, for example, by working to establish some consensus on “best practice” for methodologies, which would provide the CDM Executive Board with greater confidence that the proposed approach(es) is(are) indeed credible.

In addition, A + B International is currently developing a China Motor Model (CMM), which is a tool to define efficient/effective projects at lower transaction costs, as well as to justify the baseline. This requires that the major parameters for the design of a motor program be modeled ex ante (Figure 2) and that the program be designed to reflect quantitative information on energy savings, emission reductions and project duration and cost. Experience shows that most motor system efficiency projects would have an excellent and rapid return on investment, but still fail to overcome the barrier of indus-
trial owners' preference to keep a running system in place uninterrupted and un-
changed, even at higher cost.

The first element of the CMM consists of a quantitative description of the existing motor
park (size, age, efficiency, function, operation hours, load factor, etc.) and an
extrapolation for future sales and installation of new and replacement motor systems
during the project period.

The second element of the CMM defines typical energy efficiency data on the cost
effectiveness of systematic motor system improvements in 4 steps:

- exchange existing used motors with new high efficiency motors;
- reduce new motor size and improve components for system effectiveness;
- add variable speed control to better adapt to partial load;
- improve total motor system efficiency from transformation to pipes and ducts, etc.

Depending on quantities of motor families installed at one industrial plant and motor
size, the cost of auditing (testing, measuring, redesigning) varies greatly. Specific data
on cost effectiveness of both hardware exchanges in the above-mentioned 4 steps plus
the necessary auditing have to be taken into account.

The program design can then focus on specific motor parks that produce the best cost-
effectiveness. The key parameters suggest the following priorities:

- Old motors that have already reached their life expectancy produce no sunk cost:
  10-15 years for small motors (< 1 kW m), 20-30 years for intermediate (10 kW m)
  and 30-40 years for large motors (>100 kW m).

Figure 2: China Motor Model contents
(Brunner and Arquit Niederberger 2005)
Motors with long hours of operation (> 3'000 hours per year) deliver a faster return on investment.

Highly oversized large motor systems (> 130% typical in pumps and fans) gain efficiency through correct selection of motor size.

Motor systems without existing load management (pumps, fans, etc.), that can easily be upgraded with variable speed drives, benefit from reduced operating hours at nominal load and increased efficiency at partial load.

Large numbers of similar motors in one industrial plant (like 100 motors of 10 kW m) facilitate systematic testing, reduce engineering cost and improve replacement programs even with small and intermediate size motors.

Big typical efficiency defects in systems (leaks in compressed air systems, unnecessary high velocity in air ducts, inefficient components with high resistance in pipes for heating and hot water systems, etc.) can be systematically identified, tested and improved.

Figure 3: China Motor Model: Motor replacement and new motors (Brunner and Arquit Niederberger 2005)

Together with the specific cost of the 4-step improvement, the analysis of these typical motor before/after situations helps to quantify the crucial participation rates in replacement and new motor programs. The average kWh saved in typical motor systems, the specific cost per kWh saved and ton of CO₂ not emitted and the annual participation rate in percentage of the total motor stock give the overall energy savings and emission reduction. The necessary technical assistance provided (training, tools, mobile testing...
facilities, standard replacement schemes) and the incentives (participation on cost of audit, rebates on higher efficiency motors and components, etc.) define the speed of the program. The investments plus the total project management cost (including audits, training, tools, monitoring, etc) then define the overall cost effectiveness of the motor system program.

To be cost-effective, viable for investors/operators and credible enough to prove the program's additionality to obtain CERs, motor replacement programs must target clearly identified locations, functions and motor systems.

4 Conclusions

The CDM can give a financial boost to demand-side strategies with sound energy efficiency programs. The choice of electrical equipment for energy efficiency programs is especially important in countries with high demand growth rates and a large share of fossil thermal (in particular, coal-fired) power generation. Every kilowatt-hour saved in decentralized electrical equipment is equal to three to four kilowatt-hours in coal in central power plants.

Methodologies for the verification of energy efficiency programs are more complex than for supply side projects. This is especially true with large numbers of small-scale equipment like motor systems in dispersed locations and on a broad geographic scale. The path to a sound energy efficiency program with low transaction costs, little leakage, small "Mitnahme-Effekt" (which is not exactly the same as the free-rider effect) and solid impact is long.

The project definition has to resolve the conflict between a life cycle oriented and cost effective energy efficiency program (replace old motor with smaller high efficiency motor with variable speed drive and major improvement on the function side) versus a simple motor replacement strategy (replace old motor with new high efficiency motor of the same size). In the former, a comprehensive audit with testing by qualified personnel is necessary; in the latter, a low cost quick fix is possible.

The underlying assumptions in the baseline and the project (existing motor stock efficiency, life expectancy, annual hours of operation, oversized equipment, etc.) are crucial and need clear individual testing, sample testing or statistical verification procedures.

It is our intention to stimulate demand side programs and energy efficiency projects to apply for the CDM status in order to prove the point that every energy unit not used is the best way to reduce all loads to the environment.
5 References


MGM International: Clean Development Mechanism Project Design Document for the Electric Motor Replacement Program in Mexico. Form submitted to the CDM Executive Board 2005

Selection of Motors for End Customer Use and Installation in North America

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Abstract

This paper will discuss the challenge of equipment builders wishing to export machinery to the North American market where NEMA standards are preferred. Although IEC motors and reducers are available in North America, end users prefer motors and gear reducers with NEMA characteristics and efficiency levels.

Replacement IEC motors and gearmotors are available in North America, however they are not as readily available from distributors as NEMA motors. End users also favor separate C-face gear reducers rather than integral gearmotors. Use of readily available NEMA motors reduces plant downtime and cost when a motor fails.

There is also a perception that NEMA motors are more robust and provide more temporary overload capability than IEC motors. NEMA Premium® efficiency levels tested using IEEE 112 and CSA 390 test methods are also favored by North American end users. Because of differences in test methods, IEEE and CSA efficiencies cannot be compared with IEC efficiencies due to the differences in test methods. The Energy Policy Act defines the test methods and minimum efficiencies for motors sold in the United States. Motors with metric dimensions 1 – 200 HP must meet EPAct requirements.

There is a market for NEMA motors outside of the United States for those manufacturers building equipment for use in the North American market.

1 Introduction

Many industries rely on production machinery built in Europe. The North American motor market embraces motors built to NEMA MG 1 standards that use horsepower and U.S. customary dimensions and hardware. IEC motors with metric mountings are strange to many end users who find them a nuisance when replacements are required. Most importantly, the North American market embraces motors designed to lower the end users life cycle costs through increased efficiency and less plant downtime.

2 Energy Efficiency

Requirements

The Energy Policy Act (EPAct) mandates minimum efficiencies for 1 through 200 HP motors sold in the United States and this also applies to motors made to IEC standards. A test authority that has National Voluntary Laboratory Accreditation Program (NVLAP) certification must certify EPAct efficiencies requiring testing to IEEE 112 or CSA 390 methods and be coordinated with the U.S. Department of Energy. Few IEC motors are built to this level of performance and it is usual that a special design for North America is required.
The table below illustrates the differences between EPAct and NEMA Premium® efficiencies based on the IEEE 112 or CSA test methods. EPAct motor efficiencies are termed “Energy Efficient” and defined in NEMA MG 1-2003 Table 12-11. NEMA Premium® motor efficiencies are defined in Table 12-12 for low voltage and 12-13 for medium voltage designs.

Nominal Efficiency For 4-Pole TEFC Motors Based On IEEE 112 Test Method

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<tr>
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Preferences

As North American end users have learned more about life cycle costs, they are increasingly specifying motors built to comply with NEMA Premium® efficiency levels. According to recent NEMA survey data, premium efficient motors represent close to twenty percent of industrial motors sold in North America. IEC motors with this high efficiency level are uncommon and not easily available in Europe as these efficiency levels are well above the Eff 1 levels specified by the Committee of European Manufacturers of Electrical Machines and Power Electronics (CEMEPS).

This market transformation is because many organizations such as Hydraulic Institute (representing pump manufacturers) promote the use of NEMA Premium® efficient motors. Motor Decisions Matter and the U.S. Department of Energy / Office of Industrial
Technologies also provide end user education, best practice white papers and application guidance.

Many electric utilities have “circuit riders”, individuals that visit end users to educate them about energy efficiency and assist in conducting surveys of motors within their facility. Purchase specifications for premium motors are also addressed.

**Rebates**

On-going energy programs by electrical utilities often reward the end user for using NEMA Premium® efficient motors through a rebate program for motors and adjustable speed drives. The size of these rebate programs is huge with several states offering over $300 million in annual incentives. When looking at the repair or replace decision at the time of a motor failure, the rebate incentive is a large reason to upgrade to a premium efficient motor. Custom rebate and incentive programs are also available for plant upgrades and expansions encouraging use of premium motors and ASDs on new equipment.

### 3 Motor Performance Differences

Users have become familiar with the robust performance of NEMA design motors where integral horsepower motors generally have a very low temperature rise (40-60°C) and strong breakdown and starting torques. Rolled steel band construction is also accepted as an alternate construction through 15-20 HP (11-15 kW).

Additionally, North Americans generally specify motors having a 1.15 or greater service factor (S.F.). IEC motors typically have a 1.0 S.F. Although service factor is normally used for temporary overload conditions, NEMA MG 1 – 14.37.1 allows motors to be operated at service factor continuously when at rated voltage and frequency. Operation above rated load produce different (lower) efficiency, power factor and speed that at rated load and will have a reduced life expectancy compared to those operating at rated nameplate.

It is not unusual for North American manufacturers of industrial electric motors to offer products that significantly exceed the performance requirements defined by standards. Motors are often misapplied and overloaded. Fluctuating power supplies with high and low voltages stress motors. Lack of maintenance of the driven equipment and speeding up processes can contribute to motor overloads not easily tolerated in IEC motors that are handles by the service factor and low temperature rise in NEMA motors.

### 4 Use with Inverters

Every year the use of adjustable speed drives (ASDs) increases. Many pumps and fans now use ADSs instead of valves and dampers to control flow. As these variable torque loads are regulated, there is great potential for energy savings as well as more
precise process control. Additional rebates are available from the electrical utilities for adopting inverters on these energy saving applications.

North American voltages of 460 and 575 volts are above the normal 380-415 volt levels used in Europe. These higher voltages and the PWM waveform from the Adjustable Speed Drive (ASD) combine to stress the insulation system of most standard motors. The larger gauge magnet wire used in integral horsepower NEMA motors and Inverter-Ready motors is well suited for these ASD applications. Inverter Spike Resistant magnet wire and phase insulation are common on premium efficient motors. Many manufacturers also perform corona inception testing to ensure the integrity of the insulation system and its ability to withstand the voltage spikes defined by NEMA MG 1-2003, Part 31.4.4.2.

Most NEMA Premium® efficient motors through 100 HP are suited for use on ASDs on constant torque applications such as conveyors with 10:1 - 20:1 speed ranges. The low temperature rise and service factor of these motors provides enough margin for use in this severe duty.

5 Difference in Mounting Methods

The customary method to add a gear reducer to a motor in North America is to use a footless C-face motor bolted to a quill shaft in the reducer. European practices would often utilize an integral gearmotor through larger ratings than would be common in North America. Sub-fractional gearmotors are common in North America. On larger motors, the most common practice used everywhere is a base-mounted motor coupled to the reducer.

Right angle worm gear reducers are common, but more inline helical reducers are being installed in search of greater efficiencies. In either case, these reducers are normally available with NEMA dimensions. IEC products are more difficult to obtain through normal power transmission distributors on breakdown and is often more expensive.

6 Application-Oriented Motor Design

North American motors have evolved to include unofficial industry designations for enclosures beyond the Open-Drip Proof (IC01 / IP22) and Totally-enclosed Fan-Cooled (IC411 / IP54). NEMA defines motor enclosures and associates them with IP designations. Over many years, motor design types that are associated with the level of environmental protection for particular applications have been developed.

Severe Duty Motors

Severe duty motors are typically integral horsepower motors with cast iron housing, endplates, conduit box and fan cover. This motor design would also have corrosion
protection inside and outside for use in outdoor applications. These motors are available in high efficiency (EPAct) and NEMA Premium® efficiency levels.

A standard for severe duty motors was written by the IEEE Petroleum and Chemical Refining Committee many years ago and has evolved into IEEE Std. 841-2001 covering integral HP induction motors through 370 kW (1 – 500 HP). These motors are TENV (IC410) and TEFC (IC411) with an IP54 / IP55 level of protection. IEEE 841 has been adopted by process industries outside of the petro-chemical base that authored it. Most motors available to the IEEE 841 standard actually exceed its requirements in terms of efficiency, level of protection and added features. The standard was developed based on many years of experience in using motors in process industries. Since bearing problems cause about 60% of motor failures, much of the specification deals with mechanical features to enhance the motor bearing system and provide many years of trouble-free life. Most IEEE 841 motors actually exceed the standard because they are supplied with rotating labyrinth seals on the drive and fan ends of the motor. Also most motors are supplied with NEMA Premium® efficiency that is above what is defined in the standard. IEEE 841 motors are used in pulp and paper, cement and mining industries where a premium efficient motor with increased life and protection is desired.

Washdown Duty Motors

Other similar application-oriented motor configurations are for washdown duty, crusher duty, inverter and vector duty, and many others. For example, the smooth rolled-steel band commonly used on many North American motors is ideal for washdown applications where the finned aluminum IEC frames would have a tendency to trap food and have corrosion problems when cleaned with many of the caustic solutions used in food processing industries. Washdown motor types have been expanded to many levels of environmental protection with painted, paint-free and all-stainless housings. All are in the IC410 / 411 and IP 64-65 level of protection. Each of these configurations contains features that make the motor more suitable and robust for that particular application.

7 Conclusion

European pump manufacturers are often asked to supply motors complying with the IEEE 841 standard when supplying motors and pumps to the petroleum industry. There is no IEC equivalent to this IEEE standard. By specifying such a motor, the end user is assured of a motor built to a robust standard that will operate for many years and consume a minimum amount of energy doing so.

End users in the North American market expect such added value and features on motors for their equipment. Initial purchase price is less of an issue than the motor’s life cycle costs. Plant downtime is critical, so robust enclosures and protective features are expected. Access to replacement motors and reducers becomes an issue to companies desiring reduced plant downtime. As electric costs continue to rise, use of NEMA
Premium® efficient motors will continue to rise and there is no equivalent European efficiency standard.

8 References

[5] IEC Standard 61972, Method For Determining Losses And Efficiency Of Three-Phase Cage Induction Motors
Policies and International Issues V
Reinforcing Energy Efficiency

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Abstract

This paper is presenting energy efficiency policies in industry sector, especially for electrical motors and their interest from an industrial point of view. Despite potential energy savings for the European industrial sector estimated to be 17% of the final consumption, barriers hinder technical improvements to enhance energy efficiency. As the market cannot deliver energy efficiency, regulatory mechanisms are being developed – labelling, voluntary agreements, environmental certification, white certificates, emission trading. Fails and successes of these mechanisms depend on different parameters such as the legal aspect (mandatory or voluntary) and the scope. Initiatives and programs from different countries (the European Union, Japan, India and the USA) are compared. They are analyzed, according to their costs, their difficulties of implementation and the benefits they allow to industry. Two mechanisms are discussed in more details for motors: information web-tools, developed with the support of the European Commission for industry, mainly the Motor Challenge Program, then an on-going project, the Promot project. Other examples are proposed, which could apply to motor driven systems. The solution to reach the large savings potential relies on a mix of different mechanisms: governments need to develop balanced programs that stimulate the development of cost-effective energy efficient technology.

1 Energy savings potentials still not achieved in Industry and main barriers

Opportunities for energy saving are omnipresent in all countries, in all sectors (residential, tertiary, industry and transport) and in all product categories. Product design, installation, operation and maintenance can all contribute towards improved energy efficiency. Saving energy is not just a technical and environmental issue, it is equally important on the economical level. In Europe, an investigation has been made of the energy savings measures that are recommended on purely economical reasons, meaning that they are profitable and have a short payback time. Their potential in the European Union (EU) has been calculated to be 20% of the final energy consumption (17% in the industrial sector, 22% in the residential and tertiary sectors and 14% in the transport sector) [1].

Energy conservation has been identified [1] as a major opportunity since the first oil crisis, but numerous studies have identified barriers such as: split budgets, non aware end-users, increasing electrical appliances, practices and behavior, too cheap energy, not top management importance, etc.

These barriers hinder technical improvements to enhance energy efficiency: until 1998, energy efficiency has improved in the EU, mainly thanks to industry, by almost 10% (1% / year) but energy efficiency progress has slowed since 1998. In fact, there is no more progress in the domestic and transport sector since 1998. Meanwhile, since
1990, the total primary and final consumption increased by about 1%/year on average [2]. The European Union needs an efficient system to convert primary energy into energy services, and ultimately products and lifestyle. Efficiency is achieved through a combination of products design, engineering practice and user behavior.

A paradox is that energy efficiency is difficult to regulate, but without regulation, the market cannot deliver energy efficiency. In order to solve this dilemma, regulatory mechanisms are being developed, which improve energy efficiency. For example: labelling, voluntary agreements, environmental certification, white certificates, emission trading.

2 Existing mechanisms to develop energy efficiency

The existing mechanisms are presented, first the voluntary ones, then the mandatory.

2.1 Voluntary agreements

These are voluntary commitments, taken by industry, in order to improve energy efficiency of their products. They have been proven to work well in some sectors (e.g. the car manufacturing industries in Germany) but appear less efficient in other sectors, e.g. industrial motors systems. The key success factor of a voluntary agreement is its participation rate. Voluntary Programs need to be attractive enough to prevent unbalanced competition between participants and non participants manufacturers. Especially, markets with a lot of imports can be easily unbalanced if only domestic manufacturers are involved into the agreement. This mechanism should therefore be completed with others (regulation, financial incentives, advertising, etc.) in order to be efficient in every case.

2.2 White certificates

White Certificates promote energy efficiency by awarding certificates for energy savings interventions. Mandatory targets are set by the government after negotiations with obligated parties - power and gas suppliers. Through these quantified and compulsory targets for increased efficiency of energy use, compared with business as usual, the white certificates obtain value. Certificates can be traded on the market in order to achieve the energy saving target at minimum cost. The scheme is running at present in the United Kingdom and should start in Italy by the end of 2005, and imposes energy targets on electricity and gas distributors.

2.3 Labelling

Labelling is a soft and mandatory mechanism for informing users, which leads manufacturers of electrical appliances to design more energy efficient products. A label, put on the appliances offered for sale, informs the consumer about its energy performance
(and about other items, like water consumption or noise level). Furthermore, as consumers pay more attention to price and performance, better efficient products should not cost too much more and offer better performance than standard products. It appeared in the European Union Labelling Process that the labelling costs was equal to zero for manufacturers.

2.4 Emission Rating

12,000 European companies are covered by the ETS (Emission Trading Scheme), representing half of European CO₂ emissions. According to the EC (European Commission), the ETS is the most cost-effective mechanism to reach the Kyoto objectives: thanks to the out-coming market of emission quota, companies are expected to save more energy, because of applying better energy efficient process. Indirectly, through increased energy prices, the ETS may have an impact on energy efficiency.

2.5 Environmental Certificates

The IPPC (Integrated Pollution Prevention and Control) Directive is about minimizing pollution from various point sources throughout the European Union. All installations covered by the Directive are required to obtain an authorization (permit) from the authorities in the EU countries. Unless they have a permit, they are not allowed to operate. The permits must be based on the concept of Best Available Techniques (BAT). In many cases BAT means quite radical environmental improvements and sometimes it will be very costly for companies to adapt their plants to BAT. The IPPC Directive has been linked to the Emissions Trading Directive. Also, a BAT reference document regarding energy efficiency is in preparation, but the work has yet to start.

3 Proposed Directives

In addition, two innovative proposals for European Directives are under development to set a regulatory framework for the enhancement of energy efficiency.

3.1.1 The proposal for a Directive on Energy Services

The proposal for a Directive on Energy Services aims to increase the cost-effective and efficient end-use of energy [1]. This proposal focuses on the economical aspect of savings potential as the European final energy consumption is said to be 20% higher because of economic barriers. Thus, it proposes to remove existing barriers and develop the market of energy services in order to decrease energy intensity by 1% per year. It appears that this objective is equal to a natural trend for energy intensity which is 1% p.a.
3.1.2 The proposal for a Directive on Eco-design

The Eco-Design Directive proposal aims to introduce eco-efficiency into product design and application [3]. It is a framework directive which, in itself, does not include any new legal requirements. Through implementing measures, the directive will be able to remove some of the worst products on the market, and hopefully improve best available technology.

Despite a clear definition of eco-efficiency and many degrees of freedom to describe the implementing measures, the expected impact is the appearance of more efficiently designed products. More efficient products not only offer energy consumption for the end-users: from experience, higher productivity, lower risk of wear and tear, reduced amount of waste and resources, easier maintenance, higher product quality and low impact on the environment are expected for manufacturers.

The main risk of this Directive proposal would appear if manufacturers and system users were not involved into the process: in this case better products would not be designed, and worst products simply removed, then creating a “minus standard” on the market, which will limit the customer’s choice for better products.

4 Focus on the Motor Challenge Program and PROMOT

Motor systems in industry and service sector buildings are the largest single type of use of electricity. The Commission European Climate Change Program (ECCP) has identified motor driven systems as a major area for action to reduce electricity consumption, with a cost-effective saving potential of over 150 TWh in industry and 120 TWh in service sector buildings. Two voluntary programs, the Motor Challenge Program (MCP) and Promot, developed by the European Commission and national energy agencies of the EU, are targeting these systems in industry and big buildings.

The MCP is an on-going voluntary market frame action whereby public and private companies commit to the European Commission to reduce their electricity consumptions, thus reduce polluting emissions. The MCP was launched in February 2003 and gather more than 50 different partners and endorsers. The MCP is proposing to directors, energy managers, etc., of industries and buildings, an inventory of their equipments with an electric consumption and a first assessment of the electric savings potential. The industries are then encouraged to engaged themselves in an annual action plan to save electricity in their motor driven systems. In order to keep their MCP partners or endorsers status, they must report themselves to the Commission each year their action. The MCP endorsers are manufacturers and engineering companies that commit themselves to support the MCP and which are looking for MCP partners.

The Promot project, based on the existing knowledge, is forming and widely promoting a decision support tool for more efficient electric motor systems. The tool provides users a large variety of information, for decisions on installing a new, or replacing an old, motor system and for efficient ways of controlling it, based on energy and economic criteria. The Promot tool is developed to be accessible both on the web and on stand-
alone version. It is focusing on systems for pumping, compressed air, ventilation, drives and chillers.

5 Methods for target setting

Labelling can determine a mandatory minimum performance, either on individual products (as the European label on domestic appliances) or on a range of products (as the Japanese approach), they can be comparative labels, or only endorsement labels (a "seal of approval"). Methods can be classified in 3 dimensions: by category (label or standard), by scope (targeting individual products or a class of product), by their legal aspect (mandatory or voluntary). Methods for target setting can be divided into energy-efficiency labels and energy efficiency standards. The table below defines these two methods [4].

Table 1: Standards and labelling Methods

<table>
<thead>
<tr>
<th>Energy-efficiency labels</th>
<th>Energy-efficiency standards</th>
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<td>These are informative labels that are affixed to manufactured products and that describe a product’s energy performance (usually in the form of energy use, efficiency, or energy cost) to provide consumers with the data necessary for making informed purchases.</td>
<td>Energy-efficiency standards are procedures and regulations that prescribe the energy performance of manufactured products, sometimes prohibiting the sale of products that are less energy efficient than the minimum standard.</td>
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Labels can be classified in three different types:
- Endorsements labels are “seals of approval” according to given criteria. They generally are based on a “yes-no” cut off and offer little additional information, as the US Energy Star.
- Comparative labels allow consumer to compare performance among similar products, as the European label for domestic appliances.
- Informative-only labels provide data on a product’s performance.

Standards can be divided into three different categories:
- prescriptive standards require that a particular feature or device is installed in all new product.
- minimum energy performance standards (MEPS) prescribe minimum efficiencies (or maximum energy consumption) that manufacturers must achieve in each product, specifying the energy performance but not the technology or design details of the product.
- class-average standards specify the average efficiency of a manufactured product, allowing each manufacturer to select the level of efficiency for each model, so that the overall average is achieved.

Examples are given in section 5.1
Standards can be set to eliminate the least efficient models currently on the market, or to harmonize with another country’s standard to avoid import of inefficient products, or to encourage importers and local manufacturers to develop the most economically efficient products.

Energy labels can be used alone or in combination with energy standards. They provide a common benchmark to facilitate incentive programs. Their effectiveness depends on how the information is presented. Labels help to move the market towards higher energy efficiency. Comparative labels can provide a clear basis for other market transformation programs such as utility demand-side management.

By scope
Standards can restrict energy consumption of every individual product or control the average efficiency for a class of products. In case of a class standard, mechanisms for assessing the global result is of course more complicated, but the scheme gives more freedom to manufacturers.

By their legal aspect
Labels and standards can be either mandatory or voluntary. The combination of these different elements (category, scope and legal aspect) is relevant, since the success of a program depends on the behavior of all parties involved (importers, manufacturers, salespeople and consumers behavior).

In the following paragraphs, we present different approaches for achieving energy-efficiency targets with different combinations of above elements.

5.1 Examples

5.1.1 Removing the worst products of the market
Mandatory and non mandatory energy-efficiency standards aim to remove inefficient products from the marketplace, increasing the overall economic welfare of most consumers without limiting their choice of products.

The European Scheme to designate energy efficiency classes for low voltage AC motors has been in operation since 1999. This scheme has been established through cooperation between the European Committee of Manufacturers of Electrical Machines and Power Electronics (CEMEP) and the European Commission. It divided the motors into three classes of efficiency levels, designated [6]

- EFF3, such motors offer a very low efficiency, in parallel with an uneconomic investment in most situations, therefore they are not recommended,
- EFF2, with an average 20% energy loss reduction,
- and EFF1, with an average 40% energy loss reduction.
It aims to remove the worst products of the market (class Eff3) and to promote the best products (class Eff1). So far, the scheme resulted in a high share for Eff2 motors but Eff1 motors achieved only a few percentage market share.

5.1.2 Promoting the best available technologies (BAT)

As an example of promoting BAT, the Premium-Efficiency Motors Initiative in the US takes advantage of new motor standards required by the Energy Policy Act of 1992 (EPAct). Under this act, federal regulations require that most commercial and industrial motors manufactured or imported into the U.S. after October 1997 meet a new higher minimum standard (a standard somewhat more stringent than the EFF1 levels used in Europe).

The initiative’s goal is to encourage the widespread availability of motors that exceed this standard. The National Electrical Manufacturers Association (NEMA) is a voluntary group of electrical manufacturers that are recognized as North America’s authority on motors. The NEMA Premium label may be used with those products that meet or exceed the NEMA Premium motor efficiency guidelines. Electric motor manufacturers can sign a voluntary partnership agreement to join the program. Non-NEMA manufacturers pay a fee.

Based on data from DOE’s *United States Industrial Electric Motor Systems Market Opportunities Assessment* report, it is estimated that the NEMA Premium motor program would save 5,800 GWh of electricity and prevent the release of nearly 80 million metric tons of carbon into the atmosphere over the next ten years [8].

5.1.3 Beyond BAT

Some countries, such as Japan, give manufacturers the option to achieve different levels of energy efficiency in various models so long as the overall energy-savings target is achieved. These class-average energy standards offer manufacturers the opportunity to find creative and economically efficient ways to achieve the overall efficiency improvement. As the global energy saving depends on the relative sales of the different models with different efficiency, it requires an elaborate and sophisticated procedure for assessing and enforcing compliance with the class average target.

The Japanese Top Runner Program

In Japan, the Energy Conservation Law sets standard values for 18 types of product (in 2003) in the so called “Top Runner Program” framework. This program aims to enhance the energy consumption efficiency of product manufacturers and importers. The Top Runner Program has voluntary and mandatory aspects, according to “top runner” levels:

- Manufacturers are obliged to reach an average value for all their products per category for each predetermined target year. As in other countries, they also are obliged
to display the energy consumption in numerical values for each product concerned by the Top Runner Program.

- Manufacturers are free to participate in the Energy Saving Labelling Program.

In contrast to other countries requirements, products that fail to satisfy the standards are not removed from the market. In Japan, target standard values for energy consumption efficiency of equipment have been set since 1998 using this method. Although the Top Runner Program provides the most advanced energy-saving standards, some manufacturers have announced plans to achieve them before the target year. In fact, the Top Runner Program is seen as an opportunity for manufactures to strengthen their international competitiveness. Finally, incentives such as reduction of acquisition tax on specified products can be given by the Japanese State. The Top Runner Program method seems to be difficult to apply in Europe (expect in Switzerland, where a similar Program is running) as minimum efficiency performance standards in Europe tend to be set at unambitious levels by manufacturers.

6 A focus on Labelling Schemes

As presented above, labels put on manufactured products provide information to consumers. They also facilitate the introduction of minimum performance standards for manufacturers, as they are aware of the performance of their products and therefore best prepared for negotiations on minimum standards. Different labels have been developed, all over the world.

In the European Union, voluntary energy performance targets have been established for both domestic clothes washers and dishwashers. These targets were based directly on the energy-efficiency rating in an energy-labelling scheme and may eventually become mandatory minimum performance standards in Europe.

The Indian 5-star labels

The Indian 5-star labels [5] are comparative mandatory labels on individual products and are withdrawing the products not meeting the minimum standards.

One of the scope of the 5-star label is distribution transformers (25, 63, 100, 160, 200 kVA; 3 phase transformers). Program started in April 2002 as the Bureau of Energy Efficiency (BEE) was enacted by the Parliament to assess the feasibility of energy conservation standards for distribution transformers. Requirements have been set by a technical committee (including transmission manufacturers) under the auspices of the BEE (Bureau of Energy-Efficiency).

The current vendor base and materials available are sufficient enough to meet even star 5 performance. It was also observed that star 5 are achieved with amorphous metal economically. The cost of losses per watt will decide the star choice. It is not possible to estimate the economic attractiveness with this data as there is mix of deemed export and domestically priced tenders.
Table 2: Star rating plan for distribution transformers

<table>
<thead>
<tr>
<th>Star rating</th>
<th>Total losses at 50% load in Watt at 75°C</th>
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<tr>
<td></td>
<td>Lower limit</td>
</tr>
<tr>
<td>5 star</td>
<td>0</td>
</tr>
<tr>
<td>4 star</td>
<td>160</td>
</tr>
<tr>
<td>3 star</td>
<td>185</td>
</tr>
<tr>
<td>2 star</td>
<td>210</td>
</tr>
<tr>
<td>1 star</td>
<td>235</td>
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</table>

The energy saving potential is around 3,000 GWh per year as against the total energy sold of 316,539 GWh, if all these transformers are replaced with star 3 rating transformers. The estimated savings will be 6,000 GWh per year, if all these transformers are replaced to star 5 rating transformers.

7 Conclusion

The large energy savings potential, which could bring significant financial and environmental benefits, is difficult to reach, despite the creation of different mechanisms, more or less restrictive. Technical, financial, economical aspects are mixed together with human contradiction of behavior turning the energy efficiency enhancement into an intricate problem. The solution relies therefore not on one single type of mechanism but on a mix of different mechanisms, dealing with the technical, financial and informative points of view: energy conservation leads to better environmental, technical and financial benefits and should be considered from all these different points of view.

Governments need to develop balanced programs that remove cost-ineffective, energy wasting products from the market and stimulate the development and usage of cost-effective, energy efficient technology. Both voluntary and mandatory programs have been proven effective, depending on the sector and the economic benefits of the energy savings. Energy-efficiency labels and standards for appliances, equipment, and lighting products are one of the main policy tools to be considered by energy policy makers. The intended objective of a scheme needs to be clearly defined, i.e. whether the scheme intends to achieve an energy reduction target, to stimulate the development of new technology, to remove the worst products from the market or to harmonize standards. Many standards and labelling schemes are conservative. Methods that set ambitious targets not only achieve higher energy savings, and are better suited to yield
other benefits such as the introduction of new technology or improving the competitiveness of local manufacturers.

8 References


Ecological Benefit of Energy-Saving Motors

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Abstract
This study examines the ecological benefit of energy-saving motors by the method of integrated product planning and life-cycle-assessment (ISO EN DIN 14041). The EU is clearly aiming to increase the market share of energy-saving motors. The analysis compares whether from the environmental point of view over the life span the use of eff1-motors is indeed the ecologically better option.

When comparing the motors, raw material, production phase and the service life phase were considered. According to the scenarios assumed for the study, the daily running time varied.

The environmental impacts are measured by the most important parameters, as greenhouse-effect (CO2-equivalent), cumulative energy expenditure (CEE) and acidification potential.

As a result of this study the EU’s requirement to give blanket preference to the use of eff1- over eff2 motors can only be supported for long daily running times or life-cycles over 10 years.

1 Introduction

The Communication of the European Commission on Integrated Product Policy of July 2003 [EU, 2003] states that environmental improvements and better product performance have to go hand in hand to secure lifestyle and wellbeing sustainably. Thus, both ecological and economical aspects need to be considered for decisions in product development which should include design and production aspects as well as using conditions. Economic effects can be described by costs and profits. To assess the impacts on ecology - life cycle assessment (LCA) is a suitable new approach.

Electrical motors power a great variety of applications. So, improvements in efficiency are expected to have a considerable energy saving potential. Thus, the EU is clearly aiming to increase the market share of energy saving motors (eff1). European motor manufactures of CEMEP signed a voluntary agreement with the European Commission in order to label their standard motors with efficiency logos and in order to reduce the joint share of eff3-motors. The monitoring report 2003 documented significant efforts [Candel, 2004]. However, energy saving motors (especially eff1-motors) need more resources then eff3-motors. For instance eff1-motors material requirement is about 25% higher than those of eff2-motors, standing against an efficiency improvement of only 2 to 8%, depending on output.

This leads to the question of whether the application of eff1-motors is the ecologically better option. To give an answer to this question, two motors were examined for their environmental impacts and associated costs in a pre-study carried out by Hochschule Harz, University of Applied Sciences in association with VEM Motors GmbH. The two motors selected for this study are manufactured by VEM Motors GmbH in relatively
large numbers, the eff2 standard motor K21R 180 L4 with an output of 22 kW (efficiency 91%) and the eff1 energy-saving motor WE 1R 180 L4 with the same output of 22 kW (efficiency 93%). Apart from differences in efficiency, power factor and behaviour under part-load, the main difference between the two motors is their weight (standard motor: 170 kg; energy-saving motor: 210 kg).

This pre-study presents a life cycle analysis of electrical motors with different efficiency and different application times in order to find the ecological and economical preferable motor. Examplary for the study a fixed motor for a wastewater-pumping-station was compared over the life-cycle.

2 Methodology

Integrated product planning (IPP) is based on the understanding that any product affects the environment through all of its life phases (see Fig. 1). The complexity of the environmental impacts led to the development and application of a comprehensive methodology - “Life Cycle Assessment” (LCA) according to ISO EN DIN 14040 [ISO,1997] integrating energetical and ecological aspects.

![Figure 1: Phases of a product life cycle](image_url)

Life Cycle Assessment (LCA) can be divided into four stages:

1. Goal definition and scoping;
2. Life cycle inventory analysis (LCI);
3. Life cycle impact assessment (LCIA),
4. Interpretation

Goal definition and scoping is the first phase and will influence the time and resources required. Once the system boundaries and a functional unit has been fixed, all input and output flows including the resulting emissions are determined. Within the second phase - life cycle inventory (LCI) - the input into the process (raw material and energy) and the output (i.e. atmospheric and waterborne emissions, solid waste and other releases) are quantified and listed. The data collection is based on flow diagrams and a data collection plan. The use of specific software is recommended, the pre-study was carried out using UMBERTO.

The potential environmental and human health impacts caused by resources and releases identified during LCI will be evaluated in the Life Cycle Impact Assessment.
Phase (LCIA). LCIA can also address resource depletion. The mandatory steps are listed and further illustrated in Table 1:

- Selection and definition of impact categories
  (identify relevant environmental impact categories, e.g. global warming, acidification);
- Classification
  (assigning LCI results to the impact categories);
- Characterisation
  (modeling LCI impacts within the impact categories using science-based conversion factors);
- Normalisation;
  (expressing potential impacts in ways that can be compared);
- Weighting
  (emphasising the most important potential impacts);
- Evaluating and reporting the LCIA results.

Table 1:  Examples of Life Cycle Impact Categories

<table>
<thead>
<tr>
<th>Impact Category</th>
<th>Relevant LCI Data (i.e., classification)</th>
<th>Characterization Factor (characterization)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global warming</td>
<td>Carbon Dioxide</td>
<td>Global warming potential</td>
</tr>
<tr>
<td></td>
<td>Nitrogen Dioxide</td>
<td>Converts LCI data to carbon dioxide</td>
</tr>
<tr>
<td></td>
<td>Methane</td>
<td>equivalents</td>
</tr>
<tr>
<td></td>
<td>Chlorofluorocarbons</td>
<td></td>
</tr>
<tr>
<td></td>
<td>....</td>
<td></td>
</tr>
<tr>
<td>Acidification</td>
<td>Sulfur Oxides</td>
<td>Acidification potential</td>
</tr>
<tr>
<td></td>
<td>Nitrogen Oxides</td>
<td>Converts LCI data to hydrogen (H+)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>equivalents</td>
</tr>
</tbody>
</table>

In addition to the categories “Global warming” and “Acidification potential” the Cumulative energy expenditure in kWh (CEE) was investigated.

When comparing the eff1 and eff2 motors, the raw material production phase and the service life phase were considered. Subsequent studies will focus on the phases of manufacturing, transport and disposal/recycling. Concerning the service life phase, special attention was paid to the provision of electric energy, evaluated right back to raw material supply, and to different running times of the motors.

The daily running time was varied between one and twelve hours, because the typical running time rarely exceeds 12 hours in a production environment. If longer operation
times per day are required, usually an additional motor will be used. Additionally, two different life times of the motors, ten and fifteen years, were considered.

Complementary to environmental impacts, resulting from the utilized raw materials and during the operating life time, economical parameters like running costs and investments should be considered.

Preparation of mass flow networks, the assessment of environmental impacts and life Cycle Costing were performed using the Umberto© software which also allows an analysis of the environmental impacts by means of the UBA method.

3 Analysis of environmental impacts

The differences in the results of the impact analysis of the energy-saving motor and the standard motor were surprisingly insignificant. There is almost no or few difference between the two motors regarding environmental aspects. (see Fig. 2).

![Figure 2: Comparison of the environmental impacts of both motors (running time 10hrs/daily in 10 years)](image)

Over ten years the standard motor emits only ca. 1t or 2.2% more CO₂ than the energy-saving motor. This is due to the difference of only 2% in the efficiency and to the material consumption of the energy-saving motor which is nearly 25% higher. It is in particular the high material consumption which, at short running times, leads to a situa-
tion whereby the environmental benefits of the energy-saving motor, are no longer of any real significance. Under certain conditions the energy-saving motor even comes off worse (see Fig. 3).

To achieve a clearer distinction between the environmental impacts of the energy-saving motor and those of the standard motor, the material consumption has to be optimized. This would not only lead to ecological benefits, but would mean cost savings so that the energy-saving motor could be offered to the end user at a more attractive price.

Fig. 3 shows the reduction in ecological impacts using a eff1 motor instead of a eff2 motor over the daily running time for a life time of 10 years. At daily running time less than one hour the use of eff1 motors leads to an increased acidification potential. The higher material demand can not be compensated by the higher efficiency of 2%.

Even at higher daily running times up to 24 hours per day and a life span of 15 years the reduction of the examined environmental factors does not exceed 2.2% for this power class due to the limited improvement in efficiency. Nevertheless eff1 motors are worth to use under long life conditions with long daily running times. For example, after 15 years an eff1 motor saved 73,000 kWh and 16 t CO₂ when run 12 hours per day.
4 Outlook

Hence, the study revealed the particular measures which could be taken to achieve the European Union's goal of Integrated Product Planning. It should be followed up by subsequent studies which should focus on the manufacture of motors, transport and disposal/recycling phases and may reveal areas where improvements can potentially be made.

As a result of this study the EU's requirement to give blanket preference to the use of eff1 motors over eff2 motors can be supported only partially. In particular, the eff1 motor can be recommended for service life-cycles over ten years. For shorter service-lifes, it depends on the daily running time. For daily running times of less than two hours, it is doubtful from an ecological and economic point of view, whether preference should be given to the eff1 motor. For short daily running times the additional effort to produce eff1 motors does not pay ecologically due to the energy saving potential of only 2 to 8 % compared to standard motors (eff2).

Other parameters can achieve higher efficiency of about 15 to 20 % by improved facility design and by application of appropriate control techniques (i.e. frequency converter).

5 Literature

[Candel, 2004]

[ISO, 1997]

[ISO, 1997]

[EU, 2003]

[UBA, 1995]
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Productivity Benefits of Energy Efficiency

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Abstract
Despite the capital cost, investing in energy efficiency to reduce energy costs and increase environmental performance is good business practice. Additional benefits such as increased productivity, reduced maintenance and better product quality often outweigh the cost of energy saved and reduce the payback period by a factor of two. In this paper, examples of costs due to non efficient installations and examples of savings due to the implementation of energy efficiency measures are presented. Because of the combined effect of energy cost saving, improved environmental performance and increased productivity, it is shown that investment in high efficiency deserves high priority when allocating limited capital budgets.

1 Introduction
This paper deals with the question of the indirect benefits of energy efficiency investments. Energy conservation is not only a good business practice: indirect benefits such as increased productivity, easier maintenance, better product quality, etc. often outweigh the energy savings and reduce the payback period on investments. After describing the barriers to energy conservation, we will analyze how non-energy benefits can outweigh energy cost savings. Beside environmental and strategic benefits, we will present how efficiency and productivity are linked together. Finally, we will conclude with the different elements that should be taken into account in any investment decision.

2 Despite cost-efficient investments in energy conservation, most opportunities are mismatched
Investment in energy efficiency is well known to be cost-efficient, but such opportunities for energy conservation are often not implemented. There are many reasons for this [1], [9]:

- Although investment in conservation is efficient from a techno-economic point of view, energy is often a hidden or a small part of production cost, and hence in absolute terms the energy cost savings are relatively small compared to other investment opportunities,

- For large energy users, energy costs are more important, but these tend to be continuous production sites where there is high volume and low added value, and where the risk of changing a running process is perceived as being too high,
• In a number of cases, investment in energy efficiency is cost efficient from the socie-
tal perspective (taking into account (external) environmental costs), but not for the
company,
• Energy costs of production process are not visible to all levels of management
(maintenance, strategy, technical),
• Priority of investment is given to clear strategic business objectives,
• Split budgets which do not take into account the global energy cost resulting from
each step of the process.

At a first glance, these different points listed above would appear sufficient to stop al-
most all energy-efficiency investment decisions. But let’s take a deeper at the indirect
benefits of energy-efficiency.

One problem is that energy costs are not well known; for instance, when buying an air
compressor great attention is given to the initial price, but the larger lifetime energy
cost will rarely be calculated. In a compressed air system, reducing air-leaks, very often
a no-cost measure, can be applied and cost effective in 80% of installations and save
20% of energy consumption [2].

Figure 1: Breakdown of the lifetime costs of ownership of an air compressor

3 Energy conservation is good maintenance practice

Reliability and predictability are two key requirements for a successful manufacturing
industry, and can only be achieved with a well-planned maintenance campaign. With-
out such regular maintenance, a great deal of time, effort and money will be wasted in
emergency or reactive maintenance.

Maintaining energy efficiency and keeping machinery in good condition are closely tied
and bring substantial benefits, including increased manufacturing effectiveness, in-
creased output, improved quality, reduced maintenance costs, reduced operating costs and reduced energy costs (10% of energy cost is saved). The average cost reduction is 8% and the profitability increased by 30%, [3].

Good maintenance has many positive impacts in industrial plants, as shown in the table below.

Table 1: Impacts of maintenance

<table>
<thead>
<tr>
<th>Good maintenance brings...</th>
<th>... and leads to</th>
</tr>
</thead>
<tbody>
<tr>
<td>Company assets kept in good condition (complying with laws, regulations and standards)</td>
<td>Minimum risk of accidents</td>
</tr>
<tr>
<td>More reliable manufacturing processes</td>
<td>Minimum unplanned downtime and hence few late deliveries.</td>
</tr>
<tr>
<td>Plant operating to specification</td>
<td>High product quality and minimum re-work or scrap.</td>
</tr>
<tr>
<td>Minimised energy usage and minimum scrap product</td>
<td>Reduced operating costs.</td>
</tr>
</tbody>
</table>

It is clear that energy efficiency measures, closely tied to good maintenance practice, bring benefits beyond just simple energy savings. We will now have a look into these different benefits.

4 Non-energy benefits generally outweigh energy cost-savings

Insert 1: Examples of productivity benefits of energy efficiency measures

The evidence that non-energy savings outweighs energy cost savings appeared clearly in 77 case studies [4] with an average payback going down from 4.2 years to 1.9 years when taking productivity benefits of energy efficiency measures into account. In some cases the non-energy savings were up to three to four times higher than the energy savings.

Energy efficiency and productivity are linked together in several key subjects of interest to companies:

- Production
- Waste
- Emissions
- Operation and maintenance
- Working environment
- Other (public image, additional space, liability, etc).
As an example, the productivity effects of energy efficiency measures often include:

- A reduction of waste (product, water, hazardous waste) and materials, in addition to the direct reduction in the use of waste fuels, heat and gas,
- A reduction in dust, CO, CO$_2$, Nox and SOx emissions,
- A reduced need for engineering controls, reduced cooling requirements, increased facility reliability, reduced wear and tear on equipment and machinery,
- Increased product output, improved equipment performance, shorter process cycle times, improved product quality or purity, reduced unplaned downtime.
- A reduced need for personal protective equipment, improved lighting, reduced noise levels, improved temperature control and improved air quality
- A decreased liability, improved public image, delay or reduction of capital expenditure, additional space and improved worker morale.

Insert 2: Various benefits of energy efficiency measures

- The pulp and paper industry, food processing, industrial machinery and textile manufacturing are perfect examples for de-watering or water re-use.
- Better use of lighting through high energy efficiency equipment and installation leads to great energy savings, but also improve the working environment through better lighting quality.

The Motor Challenge Programme, launched in February 2003, which gathers 50 industrial partners, aims to reduce costs and increase reliability and quality through high efficiency motors in the drive, compressed air, speed control, fans and pumps areas. Detailed information is available at http://energyefficiency.jrc.cec.eu.int/Motorchallenge/

The GreenLight program is focusing on efficient lighting in buildings. It is an on-going voluntary program whereby private and public organizations commit to the European Commission to reduce their lighting energy use, thus reducing polluting emissions. GreenLight was launched in February 2000 and now has 186 different partners. Detailed information is available at www.eu-greenlight.org.

5 Including productivity effects in investments decisions

In view of the clear indirect benefits of improved energy efficiency, it is important that these other benefits are used in the evaluation of energy efficiency investments. However, in practice it is difficult and time consuming to quantify what many of these will be. Frequently the temptation is therefore to ignore them, but even very conservative estimates or just qualitative statements are worth while in supporting a case for investment.
In Nogent-sur-Oise (Fr), a company is manufacturing aluminum cylinder heads, using several compressed air systems. Different energy efficiency measures have been applied:

- regulation,
- decreasing pressure,
- reducing air leaks,
- changing modus operandi.

In addition to the energy saving from compressed air production (see figure below), two different productivity benefits appear:

1. the energy efficiency measures allow an increase in production without investing in new industrial equipment,
2. decrease the maintenance costs.

![Figure 2: Investments, consumptions and other benefits](image)

6 Energy efficiency brings extra benefits on the strategic side

Beside the productivity benefits of energy efficiency measures, there are other extra benefits which should be mentioned, even if they can’t be quantified into economic terms. For instance, the improved environmental performance reached through energy efficient processes allow companies to anticipate any new regulation, facilitate discussions on environmental permits with local authorities, and finally bring a positive public image.
At Chamforgueil (Fr), a company is manufacturing electrical equipment, using several compressed air systems. Only one action has been successfully implemented: variable speed drive on the compressed air systems. In addition to the direct energy savings, this action increased the work’s organization’s flexibility and the public image of the company. In recognition of the company’s efforts, the local authority has given them a Regional Environment Award.

<table>
<thead>
<tr>
<th>25 200 € invested in equipment for energy efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.4 years of payback time</td>
</tr>
<tr>
<td>7 330 euros saved par year by direct energy savings,</td>
</tr>
<tr>
<td>20% of energy saved on compressed air production</td>
</tr>
<tr>
<td>Increase in work organization flexibility</td>
</tr>
<tr>
<td>Gain of the Regional Environment Award</td>
</tr>
</tbody>
</table>

Figure 3: Investments, consumptions and positive image

7 Conclusion, five elements should be taken into account in investments decisions

Energy efficiency investments are often simply seen as operating investments, whereas they should be considered from a larger view as a strategic investment: energy efficiency and productivity are often linked together at each step of the life cycle of the product. Guaranteeing or increasing production must also be taken into account.

Therefore five elements should be taken into account in investments decisions:

- the investment cost itself,
- the productivity cost savings,
- the energy cost savings (which are quantified elements),
- the environmental aspects (which can be quantified too),
- and the risk of a process shutdown (a strategic element for any industry).
8 References


[7] Joe Romm, Center for Energy and Climate Solutions

[8] Hugh Falkner, AEA

The List and the Activities of AssEI in the Promotion of High Efficiency Induction Motors

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Abstract

Motor Repairers are an essential part of our modern industrial infrastructure because they can and do provide the quick and local service which is required by motor users when a motor fails. In Italy a trade association of motor repair shops has been founded: the Associazione Elettromeccanici Italiani (AssEI), whose aim is to give prominence to professionalism of the partners stimulating also the interaction and co-operation between Repairers and motor Manufacturers.

The papers presents some significant initiatives of AssEI above all in the promotion ad use of high efficiency motors.

1 Introduction

In the past little consideration has been given, in Europe, to the impact of repair methods on motor efficiency.

It is widely accepted that it is cheaper to repair failed motors above 7.5 kW than to replace them (Project Report 1999). When a motor fails, the main concern of most motor users and Repairers is to get the motor back into service as quickly and inexpensively as possible. This situations sometimes lead to the use of repair processes, which can significantly reduce the motor efficiency. However, the increasing awareness of the huge amount of electricity consumed by electric motors, coupled with the increasing focus on Energy-Efficiency and emergence of Energy-Efficient Motors, has highlighted the effects that motor repair can have on efficiency.

Laboratory testing studies (Project Report 1999) confirm that motor repair practices reduce motor efficiency typically between 0.5 and 1%, and sometimes up to 4%. Most of the efficiency reduction has been assumed to result from increased iron losses caused by burning out the old winding at too high temperature; however incorrect configuration or sizing of the new winding can have an equal or greater effect.

If so, the motor user’s subsequent energy costs will be increased and this strengthens the case for replacing rather than rewinding the failed motor.

This is because the rewinding processes are in general not as well controlled as the original design and production of the motors. Additionally, some rewind shops do not have the equipment or the information necessary to repair every type of motor to the Manufacturers specifications.
Most users do not pay attention or do not know what happens during the repair process, and they do not worry about the possible efficiency drop after repair. They are usually unaware of the impact on the energy bill due to reduced efficiency levels of electric motors, after repair. It is known that the motor repair market represents between 2 and 3 times (in terms of kW) the new motor market: particularly every kW bought (new motors) about 2÷3 kW will be repaired. This is why the improvement of the repair market is so important in order to decrease the operating cost of motor users.

In order to overcome the barriers to energy-efficient repair of low voltage motors, to develop strategies for maintaining motor efficiency during repair and for a right motor maintenance, a trade association of motor repair shops has been founded in Italy, since 2004: the Associazione Elettromeccanici Italiani (AssEI).

2 The aims of AssEI

The Associazione Elettromeccanici Italiani gathers about the 50% of Italian Repairers from every part of the country. The aim of AssEI is to give prominence to professionalism of the partners and promote this sector, stimulating also the interaction and cooperation between Repairers and motor Manufacturers.

The activities of AssEI are financed by enrolments, public financing and contributions by electromechanical Companies.

The AssEI well knows that the reduction of energy consumption and, as result, the protection of our environment is one of the most important concerns of reasonable technical activities. For this reason AssEI is deeply entangled to organize seminars and courses in the electromechanical field in order to point out, among the partners, the importance of a right motor repair.

Motor Repairers are an essential part of our modern industrial infrastructure because they can and do provide the quick and local service which is required by motor users when a motor fails. However, if by repairing the motor its efficiency is reduced and subsequent operating costs increased, the long term value of the repairer’s work is diminished.

Although AssEI has been recently established, several initiatives have been undertaken whose aims can be synthesized as follows:

- to promote the use of high efficiency motors in the industrial sectors and Public bodies;
- to repair motors and electric equipments according to procedures consistent with the aim of the energy efficiency.
- to spread the culture of energy efficiency in the use of the electric power not only in Italy but also in foreign countries in Asia and East Europe;
- to establish local assistance agencies to support the Italian contractors in the business relations with local partners for the sale and/or repairing of electromechanical equipments.
In Europe exist several Repairers Associations, but most of them are mainly engaged in trade-union activities for the Repairers protection: AssEI is one of few deeply involved in the energy savings and it has focused its activity on this specific sector.

3 The use of high efficiency motors and the role of the Repairers

The European Scheme to designate energy efficiency classes for low voltage AC motors has been in operation since 1999. It is based on a voluntary agreement between the European Commission and CEMEP, the European Committee of Manufacturers of Electrical Machines and Power Electronics. This Scheme classifies induction motors into three efficiency bands, from Eff3 (lowest) to Eff1 (highest).

The promotion on the use and diffusion of high efficiency motors in Eff2 or Eff1 classes represents one of the more significant initiatives of AssEI. It consists of a right dissemination giving to Repairers clear information on the success in the adoption of higher efficiency motors even if these actions should overcome some market barriers in the diffusion of energy efficiency in the electric motors. These barriers can be summarized as follows:

- pay-back time could be too long due to low electricity price;
- not all parties in the supply chain are interested;
- split budgets;
- oversizing due to unknown mechanical load characteristics;
- shortage of qualified and specialized staff in the energy efficiency sector;
- the damage motors are often replaced with motors of the same type.

In order to pursue the energy efficiency in the sector of electric motors, the barriers that prevent the diffusion of these motors should be removed. In this context the Repairers play a significant role since their main activities concern not only:

- the repair of damaged motors and keep them within the original specification;
- the maintenance and supply of spare parts;

but also the retail of motors.

All these activities have a strong relapse on the energy efficiency and the Association together with the Repairers will start up the promotion on the use of high efficiency motors. Moreover, the Repairers have the responsibility to choice the repair or substitution of the motor and, in the case of substitution, they could propose motors in Eff 2 or Eff 1 classes rather than a standard motors (in Eff 3).
4 Some actions of AssEI

4.1 The training Centre

It is well known that the Repairers should follow a best practice motor repair scheme in order to guarantee a quality repair consistent with the aim of the energy efficiency, and for this reason AssEI will put into action courses and seminars, with a very practical agenda, that represent the main tool for distributing information.

For these purpose, AssEI will manage a qualified training centre in Arese (Milan), for the motors maintenance and repairing and above all the energy saving in the electric motors.

This area was used, up to 2000, for the manufacture of mass-produced cars and now has been converted into business area and training centre; it represents not only a good example of urban reinstatement but also a substantial contribution to the professional growth of the people.

The Regione Lombardia has entrusted to AssEI about 15000 squared meter of this area, modifying the buildings and sheds to obtain:

- laboratories;
- lecture-halls;
- conference hall;
- meeting rooms;
- show room;
- library;
- administrative offices.

The training center will be at Repairer's disposal not only for the courses but also for technical conferences, meeting with other partners, motor Manufacturers or customers and for any other activities concerning the motor repair (e.g. motors testing).

Moreover, the experience of qualified consultants will allow to AssEI to provide all technical assistance to Repairers and organize training courses, at different levels, together with ENAIP – Servizi Formativi, that is a national Organization for training.

The opportunity of a qualified training centre will allow also to awaken the suppliers for an informative campaign towards the users about all the actions concerning the energy saving. These actions could be oriented towards the development of energetic monitoring activities by means of specific software from technical consultants, or the opportunity to find adequate financings for the energy efficiency.
4.2 Actions in the East Europe and Asiatic countries for the international co-operation

In the last years many Asiatic countries like as China and India have had a significant economic growth. For these countries it is essential to start all the actions oriented to the improvement of the energy efficiency above all in the electric sector, where the motors consume about 60 ÷ 80 % of the electric energy used in the industry. For this reason, particular attention should be paid to the motors repair and maintenance.

AssEI intends to start an international co-operation and operate in East Europe, China and India in order to dwell the culture of energy saving in the use of electric energy, and particularly:

- to promote the use of high efficiency motors;
- to repair motors and electric equipments according to procedures consistent with the aim of the energy efficiency.

This last point requires an adequate professional training of qualified Repairers in order to create a local capability able to execute maintenance operations and repair.

These actions certainly will give rise to significant benefits in a short time and will improve the commercial exchanges among Italy and these countries about high efficiency components; moreover these interventions will have, in a long time, a good repercussion on the local environmental conditions due to a reduction in the consumed energy and fossil fuel.

The international co-operation will concern four intervention areas:

- development of human resources;
- establishment of local agencies and/or consortiums for the technical assistance;
- development of facilities for the local Italian firms;
- development of marketing actions among Italy and foreign countries for the diffusion of high efficiency equipments.

References

Management Issues
Local Learning Networks – an Effective Instrument to Reduce Transaction Costs for Decisions to Invest in Efficient Motor Systems

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Abstract

Profitable efficiency potentials are often not exploited in industry, since management does not tend to focus on energy issues. Transaction costs are high, especially for “minor” investments in electric motor systems. Sharing experiences between companies reveals possibilities for reducing the transaction costs involved and convincing management to pay more attention to energy efficiency. Learning networks of regionally organised companies achieved substantial savings by sharing a senior engineer, who provided on-the-spot consulting, expert information, and by monitoring the three monthly half day meetings when they share their experiences of their most recent efficiency investments.

The results of some evaluations show that the efficiency potentials of electric motor systems and lighting have been specifically taken up by the companies with substantial progress being made compared to the business-as-usual efficiency progress in electricity use. The reasons for these achievements are discussed and conclusions are drawn about the opportunities and limits of this instrument. Finally, a recommendation is made that this instrument be implemented at the EU level.

1 Introduction – end use efficiency out of focus?

Electricity continues to gain an increasing share of final energy use in all countries, despite its use placing an extra burden on the energy economy and the environment. Its generation is linked with relatively low efficiencies compared to oil refining or direct gas use and the environmental burden is particularly high when the primary energy involved is fossil or nuclear. About one third of total energy-related CO₂ emissions stem from increasing shares of power generation (together with road transportation in the past). The European Commission and many governments of member states are concentrating on either shifting the share of primary energy towards natural gas or renewables or on CO₂ capture and storage of large centralised power plants. But little attention has been paid to using electricity more efficiently in all final energy sectors. Of course, the energy-efficiency labelling of some domestic appliances was introduced more than 10 years ago; but the standards have not been updated to keep abreast with technological progress and labelling has not been extended to electrical appliances other than traditional household appliances (except for high efficiency electrical motors).

Consulting engineers usually return from on-site visits with substantial energy efficiency potentials that are easy to realise and usually have high rates of internal return (Romm 1999). The limited realization of profitable efficiency potentials has been the subject of
discussions about obstacles and market imperfections for a decade (IPCC 2002), and the heterogeneity of these obstacles and potentials has been tackled by sets of several policy measures and instruments (Levine et al. 1995).

However, substantial obstacles and lost opportunities of companies are still prevalent, even in cases where intelligent energy efficiency policies are in place (Romm 1999; DeCanio 1998, IPCC 2002). Surveys and interviews show that often the attention given to energy efficiency investments in companies is very low and heavily influenced by the priorities of those responsible for management of the site or the enterprise (Rahmesohl 2000, DeGroot 2002). In other cases, the project-based economic evaluations often do not consider the relatively high transaction costs of the investor and also the substantial risks involved in the case of long-term investments; both aspects may be decisive for small efficiency investments (Ostertag 2002).

There are several good reasons for this priority setting of companies (concentration on main competences, focus on ever increasing wages, on product quality and timely delivery); but there are other reasons that are not covered by the theories of business economics or micro economics:

- traditional investment priorities steer the motivation and behaviour of the staff and determine the career of the young engineers and their efforts; energy engineers often have difficulties to “make an convincing case” to the management (Schmid 2004);
- the co-benefits of energy-efficient new technologies are rarely identified and not included in the profitability calculations by the energy or process engineers due to the lack of a systemic view of the whole production site and possible changes related to the efficiency investments (Madlener/Jochem 2004);
- management is often not aware that the workforce may suffer from criticisms made by friends or relatives that they are working in a “polluting” or wasteful industrial site. These “soft” psycho-social, motivational, and behavioural aspects of the energy efficiency of the responsible management and energy engineers have scarcely been analysed except by some sociologists and psychologists in the 1990s (e.g. Jochem/Sathaye/Bouille 2000, Flury-Kleubler et al. 2001).

Social relations such as competitive behaviour, mutual estimation and acceptance not only play a role between companies, but also internally within a company. Efforts to improve energy efficiency are influenced by the intrinsic motivation of companies’ actors and decision makers, the interaction between those responsible for energy and the management, the internal stimuli of key actors and their prestige and persuasive power as well as the company (InterSEE 1998, Schmid 2004).

Given the complex innovation situation of energy efficiency investments or organisational measures in industrial companies, this paper follows two major objectives:

(1) to broaden the existing concept of obstacles and market imperfections related to energy efficiency potentials. This concept has been developed over the last three decades, largely by engineers and systems analysts in the earlier period and
then refined by sociological and psychological approaches in the 1990s (see IPCC 2002);

(2) to demonstrate this new concept in practice by reporting on the results of ongoing learning networks of regionally organised companies interested in mutual learning and sharing of experiences in energy efficiency, also called "Energy Tables". This interesting instrument focuses on reducing the transaction costs of companies with an annual energy bill of at least 150,000 € and was first initiated in Switzerland in the early 1990s (Bürki 1999) and recently introduced in other countries such as Germany (Jochem/Gruber 2003).

First progress has been reported in an earlier publication (Jochem/Gruber 2004), and this paper will focus on two aspects – efficient electricity use and the preconditions for a successful implementation of learning networks of this kind.

2 Underlying theoretical concepts and implementing learning networks

In a previous publication (Jochem/Gruber 2004), the underlying theoretical framework of the Energy Tables has been outlined in more detail, and its major components will be briefly summarised here in order to trace the underlying concepts to the implementation of the networks existing in Switzerland and Germany.

• The heuristic approach of innovation systems is used to demonstrate the network of actors who are involved in bringing about an innovation (Kuhlmann XX). An investment in new energy-efficient technologies does not come about due to a decision of the management of a company, but is the result of a complex interplay between many actors who may have different weights in influencing a decision in a particular case: consultants, equipment suppliers, installers, architects, outside maintenance staff, key accountant of energy suppliers or the cooperating bank, investment decisions of competitors or of management colleagues in the region.

• One element of the concept follows the dynamics of a product or investment cycle, applying them in two dimensions: (1) new and reliable efficiency technologies just being introduced to the market are presented on the initiative of the senior engineer and (2) changes to the production and product quality at the production site caused by the efficiency investment are analysed in order to identify risks and co-benefits which are often neglected in energy efficiency investment considerations.

• The concept also considers aspects of innovation research, i.e. the concept of first movers, followers, and late applicants with the competences and motivations of those types of companies and their management, as well as the size of the company and its potential to engage specialists in the field of efficient energy use as internal staff or external consultants.

• Finally, the concept also integrates concepts of social and individual psychology: social dynamics such as mutual affirmation within a company and among compa-
nies (or administrations or private households), social cohesion, responsibility and sanctions once a common target has been agreed upon, low competitive behaviour in acquainted groups as well as individual behaviour such as the motivation of professional careers, the motivation of experts to share their knowledge with colleagues often working in small and medium-sized companies, or the motivation of management with regard to achieving a good acceptance of the company at its production location (Schmid 2004, Flury-Kleubler et al. 2001).

It has to be stressed that this attempt to use existing theoretical concepts of innovation and socio-psychological research only began quite recently during the last few years whereas the first successful performance of Energy Tables already occurred in Swiss cities in the 1990s (Bürki 1999). However, the theoretical concepts are now being applied in order to understand the successes and limitations of this instrument (and instruments that have to be used simultaneously) and to improve the efficiency and the sustainability of those networks.

The better understanding of the learning networks in efficient energy use is a gradually developing process based on several ex post evaluations of the Swiss networks (called EnergyModel Switzerland) and the ongoing evaluation of the German EnergyModel Hohenlohe (Graf 1996, Kristof et al. 1999, Konersmann 2002; Jochem/Gruber 2004b).

Energy Tables in Switzerland – local learning networks in the context of Kyoto

After more than 15 years of experience with the first Energy Table in Zurich, around 200 companies were participating in almost 20 locally organised networks by 1999. This process has been reaffirmed by the foundation of the Energy Agency for Industry (EnAW) with its major role of supporting the industrial and service sectors by reducing energy-related CO₂ emissions in line with the target set in the Swiss CO₂ law (decrease of fossil fuel-based CO₂ emissions by 15 % between 1990 and 2010). The Agency was necessary as the CO₂ law levies a surcharge on fossil fuels (now set at 35 CHF/t CO₂) and companies not willing to play the surcharge may be exempted from it under a target agreement.

One major role of the Energy Agency for industry is acting as an intermediary to negotiate such target agreements with the federal government for individual companies or branches. To achieve the targets, the EnAW relies heavily on the Energy Tables as a successful means for larger companies and on benchmark courses for small and medium sized companies. About 30 Energy Tables are now working, and more than 1,000 companies are involved in this scheme, representing 3 million tonnes of CO₂ or one quarter of the total CO₂ emissions of industry and services. The target agreements are mostly based on energy efficiency improvements over a given period of time, e.g. four years, or substitution options for fossil fuels such as industrial organic wastes, renewables, or electricity. The target agreements amount to 0.47 million tonnes of CO₂ or 18 % of present emissions. (BFE 2004) The Energy Agency for Industry is supported financially by the Swiss government with 2 million CHF per year and some 7.8 million
CHF in contributions from companies as direct payments or staff contributions (BFE 2004).

The Energy Tables were partially subsidised by the Swiss government in the first few years of their existence and a few new ones still are, but they then become financially self-supporting after some years with contributions of some 3 000 to 20 000 CHF per participating company and year, depending on the size or the energy costs of a member company. The average annual energy cost savings were 165 000 CHF (or 100 000 Euro) per company. Similar rules were set up this year by the German federal state government of Baden-Württemberg.

*Energy Tables in Germany – local learning networks in the context of innovation and climate change policy*

Starting from the positive Swiss experiences, a first learning efficiency network was launched in the Hohenlohe region by the government of Baden-Württemberg in mid 2002. This network was designed and monitored in an ongoing evaluation by the authors. The network started with 17 companies of very different size in 20 sites representing a broad range of industrial and service sectors. After three years, almost all the small companies (with annual energy costs below 100 000 €) stopped participating, usually with the arguments that they wanted to focus on the investments planned before getting additional ideas and that the four sessions each year were too much for their staff capacity. But they still want to be involved in the yearly energy efficiency progress assessment to maintain the momentum within the network and their own company.

The evaluation of the Energy Table in Hohenlohe, a region in the North-East of Baden-Württemberg was so convincing (see below) that the Ministry of Environment and Transportation in Stuttgart set up a financial incentive programme providing efficiency learning networks with one third of the total cost (including a scientific evaluation) for two years. Under this new programme, a second Energy Table started operating in Ulm in April this year.

Box 1: The typical set-up of a local efficiency learning network, implemented in Switzerland and Germany

- a one to two day initial consulting for each company by the moderator with a final written report and recommendations to be followed up in the following years,
- discussion and agreement on a joint target for energy efficiency improvement and CO₂ emission reduction on the basis of the potentials discovered in the initial consulting period among the participating companies,
- regular meetings of the 17 companies (four times per year) being monitored by a senior engineer to encourage the participants towards sharing their experiences, to bring in new technical information and organisational measures, also by inviting experts for selected topics (e.g. compressed air, cooling, lighting, high efficiency electrical motors, business economics),
- ...
... meetings in small groups on specific technical options such as heat recovery, compressed air, electronic control of electrical drives, cooling, joint procurement,

- installation of a telephone hotline for spontaneous questions and technical and organisational advice by an energy consultant,

- yearly monitoring of the energy demand, the related CO₂ emissions and the measures planned and realised for each participating company,

- meetings of the top management of the companies once a year to listen to the performance report and to decide on major joint activities of the Energy Table,

- scientific monitoring and evaluation of the whole process of networking and its results based on in-depth interviews with the participants, analysis of the consultation process and participating observation in the meetings.

3 Results achieved – electricity efficiencies in particular

The total energy use of all the companies involved was 731 TJ (i.e. about 9 million Euro in energy costs per year) in the base year 2001, of which almost 69% was accounted for by electricity (502 PJ) and 31% by fuels (see Table 1). Despite the large energy intensity differences between the companies, an energy efficiency potential of 6 to 8 per cent on average was identified during the initial consultation in 2002 and the participants agreed on a joint efficiency target of 7% of energy savings and 8% CO₂ emissions reduction (at constant production) by 2005 in year by year steps.

During the first year the companies achieved a joint efficiency improvement of 1.4% and even a joint CO₂ reduction of 2.5% – calculated under constant production and weather conditions. This somewhat unexpected result was mainly caused by immediate organisational electricity saving measures (German electricity has a relatively high CO₂-intensity of 161 kg CO₂/GJel) and by improved fuel efficiencies.

It is interesting to note that this pattern of efficiency prevailed over the three year period from 2001 to 2004: whereas the production of all 20 sites increased by 11.3%, electricity demand only increased by 2.2% in this period (see Table), which means an improvement of electricity productivity of 3% per year. The carbon intensity is similarly positive at a declining rate of 2.5% per year. These achievements were quite unexpected at the beginning of the Energy Table, but the reasons become clearer after analysing the high potentials of efficient electricity use in compressed air systems, better control of pumps, fans and other motor driven applications and improved lighting, which can all be realised in a short period.
Table 1: Final energy and electricity use and CO₂ emissions of the Energy Table
Hohenlohe, 2001 to 2004

<table>
<thead>
<tr>
<th></th>
<th>2001</th>
<th>2002</th>
<th>2003</th>
<th>2004</th>
<th>change</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2001 - 2004</td>
</tr>
<tr>
<td>Measured energy data</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- total energy use</td>
<td>731.2</td>
<td>733.7</td>
<td>761.6</td>
<td>784.3</td>
<td>+ 7.1 %</td>
</tr>
<tr>
<td>- electricity use</td>
<td>502.4</td>
<td>499.5</td>
<td>502.2</td>
<td>513.5</td>
<td>+ 2.2 %</td>
</tr>
<tr>
<td>total energy (weather adjusted)</td>
<td>731.2</td>
<td>740.9</td>
<td>761.6</td>
<td>782.8</td>
<td>+ 6.8 %</td>
</tr>
<tr>
<td>CO₂ emissions in Mt ²)</td>
<td>95.2</td>
<td>95.3</td>
<td>96.9</td>
<td>98.9</td>
<td>+ 3.9 %</td>
</tr>
<tr>
<td>Production in billion €</td>
<td>1.489</td>
<td>1.534</td>
<td>1.588</td>
<td>1.654</td>
<td>+ 11.1 %</td>
</tr>
</tbody>
</table>

1) subject to minor changes due to statistical corrections (including effects of product stocks, insufficiently used capacities, changes in product structure)

2) direct and indirect emissions (due to electricity generation)

One explanation for the unexpected electricity savings is some energy savings due to structural changes at the 20 sites: the energy-intensive companies grew somewhat slower during these three years than the average production of all 20 participants, and some of the companies increased their electricity or fuel intensity by changing production processes or the structure of their product portfolio. The net effect of these structural changes resulted in a decrease in electricity use by 5 % of the total electricity savings or 1.5 TJ.

In absolute terms, energy savings due to efficiency improvements after the first three years amounted to some 28 TJ (almost entirely electricity savings). In monetary terms, the saved energy costs were around 450,000 € in 2004 that could be used to refinance the capital cost for the investments or to pay for the organisational cost of labour. This result confirms the substantial potential of immediate organisational measures realised between 2002 and 2004. Investments in fuel and heat efficiency are very much related to the production processes or heating buildings with very long-term re-investment cycles that cannot be changed if stranded investments are to be avoided.

These results also reflect the outcome of the survey on the individual measures of companies which showed a high preference for more efficient electricity use (e.g. reducing the pressure of compressed air systems, identifying air losses which accounted for almost 15 %, better control of electrical systems, replacing mechanical control of gaseous and fluid streams by variable speed drives, substituting normal electrical motors by high efficiency ones, investments in lighting with high efficiency improvements, reshaping piping and air conduct systems using improved hydrodynamic planning tools and improved outlets of air-conditioning systems). These investments were supported by organisational measures such as improved maintenance, additional measurements and energy data analysis as well as the separate billing of individual product lines and
departments which reduced the electricity cost not allocated to individual production lines.

High-efficiency motor drives have been an issue in almost all companies whenever there was a substantial relevance of motors. Six companies (out of 17) said in the interviews that they already shifted towards speed-controlled motors, but the consultants still found additional potentials in these companies. Within the first phase of the project, one company completed the implementation of high-efficiency motors (7.5 kW): three of 12 identified motors have already been replaced, the others will follow. A producer of gear units included high-efficiency motor drives in the duties for future purchases of equipment, another large company started checking its hundreds of motors in practically all production equipment, especially in the galvanic systems, with 1–5 kW each and a high number of operating hours. In a foundry, motors in continuously running pumps are being replaced step by step.

All of these measures resulted from the initial consultations and the decisions were supported by a lecture on high-efficiency motors in one of the Energy Table meetings. None of the energy managers of the 17 companies knew of high efficient motors before the learning network started which sheds a light on the marketing of the producers or the trade companies of electrical motors. The trade companies do not have the high efficiency motors on stock because the demand is low and because they want to minimise their capital cost of the stock. This led to the idea that one large company of the learning network should run a joint stock for high efficiency electrical motors sharing the cost among the 17 partner companies and a trade company. This idea has not yet materialised, but may be operating in 2006.

Further suggestions of the consultants still are in a planning phase: high-efficiency motors in three cases for ventilation systems and in one case for cooling-water pumps. An investment in a speed-control for the ventilation motor is still postponed due to high prices which the equipment producers offered. Another interesting result of the discussions were the intention of an participating company, which produces itself equipment with electrical motor drives, to install high-efficiency motors in its own products.

Considering the targets of the four year period, 7 % improvement of energy use and 8 % improvement in specific CO₂-emissions, the high electricity savings contributed to a faster achievement of the CO₂ reduction target than jointly decided upon in January 2003 (see Figure 1). It is therefore likely that the CO₂ reduction target will be met earlier than the end of 2005. On the other hand, the energy efficiency target (remaining 2.5 %) in 2005 is quite ambitious and at risk due to a lower than average capacity load and other priorities of the companies in times of uncertain economic development.
4 Preconditions and factors of successful learning networks

The generation of a learning network on energy efficiency is not an easy task if external boundary conditions such as the Swiss CO₂ law are not present to convince companies to get involved in order to, e.g. avoid a CO₂ surcharge by participating in such a network in order to meet the agreed target at minimum cost. As this external incentive is an exception, one has to consider other favourable circumstances which should be targeted in order to successfully generate a locally operating learning network on energy efficiency:

- As the transaction costs for participating in the Energy Table several times per year have to be considered, a company should have annual energy costs of at least 100 000 €.

- For the success of the Energy Table, it is important that the representatives sent by the companies to the meetings of the learning network participate in an active and constructive way. Almost all the companies found the meetings very helpful to expand their horizons and to discuss new topics. Several judged the exchange of experiences within the group to be a key element of the whole activity and a stimulus for taking energy-efficiency actions. The participants thought it important that the discussions are open and that participants can speak frankly about success, failure and how problems were solved.
• The top management of the participating companies should be included in the flow of information and participate in the network once a year.

• When launching a new network, one precondition is an institutional "catalyst", i.e. an institution trusted by local companies which appoints one person dedicated to the idea of initiating the learning network. The network's chances for success are extremely low if there is a lack of confidence or a dedicated person.

• There should be a professional, knowledgeable senior engineer to moderate the meetings, who knows the production sites of the participating companies and is dedicated to his task.

• The institution organising the hotline, the meetings and the information flow should operate at a high professional standard.

• The company group should not be too heterogeneous with respect to size or branch even though the heterogeneous composition was accepted or even appreciated by the participants, "everybody can learn from the others".

• One should not always expect the Energy Table to initiate completely new measures. Some companies received confirmation of their own decisions rather than completely new suggestions. This was however an important aid for getting some company managers to agree to the implementation of planned measures.

• A convincing factor in some companies was the common target setting. The whole project leads to a systematic inventory of the main points of energy consumption and of possible solutions and their optimisation. Small measures, often organisational ones, were also considered, which otherwise would have received no attention in the day-to-day running of the business.

A further indicator of the success of the Energy Table was the fact that all the participants continued their co-operation after the first phase of the initial consulting and invested up to 5,000 Euro – according to the company's size – in participation during the second phase. At the end of the two years the majority of participants want to continue their Energy Table activities.

A further measure is planned: the co-operative procurement of energy efficiency goods. Highly-efficient electric motors, energy-saving lamps and highly-insulated windows are the most promising technologies for this purpose. This measure was discussed several times during the meetings, but was postponed due to time restrictions, the handling of different product specifications and logistic problems.

5 Conclusions

In almost all companies, there is a high potential of profitable energy efficiency. Even energy managers from large companies did not know about all the new innovations of efficient energy use and were able to inform themselves about the new options faster than was the case without the Energy Table. The high electricity efficiency improve-
ments were unexpected. These amounted to 2.5% per year compared to less than 1% per year on average in industry.

The sharing of experiences increased with increasing duration and trust within the group of the 17 participating companies, even among a few competing companies with regard to cross-cutting technologies. The joint efficiency and CO₂ reduction targets were useful to continue to emphasise the issue of energy efficiency and energy cost reduction at a higher level of priority in the companies and to more easily convince management about planned investments.

The participants confirmed a substantial reduction of transaction costs and faster implementation of measures as a result of the meetings, sharing experiences and know-how, and the experts invited. Some of the participating companies expect an improved image from the Energy Table. Because of the positive results in Switzerland and Germany, these locally organised learning networks are considered to be an excellent instrument for reducing the transaction costs of energy efficiency planning and decision making in cross-cutting energy issues. It is recommended that they be considered by the European Commission and the governments of the member states as a potentially very effective instrument for picking the "low hanging fruits" of efficient energy use and especially of efficient electricity use in the short term.

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Technological Management of Efficient Use of Electric Motors: An Important Tool in Competitiveness

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Abstract

Electric motors take near 80% of electricity energy used in an industry, then the efficient use of electric motors allows to reduce production costs and increase competitiveness of the industry. By other side technology management is an administration activity in order to increase productivity and competitiveness through the innovation and correct organization of technology, information and cost. Therefore it is important to establish a relation between the efficient use of electric motor technology and the technological management.

The experience shows that the technologies of efficient use of electric motor applied to industry allows to obtain a decrease of the energy consume between 10 to 20 percent. However, the electric motor is only a part of the production process and it is not so important its influence with respect to the total cost of production.

Starting from the segregation of all the activities of the productive process, it is shown that in order to improve business production and competitiveness, managers needs others additional indicators beside energy costs, indicators related with technological innovation and management. In this paper, the authors are proposing several indicators in order to be use by managers in taking decisions to improve the competitiveness of business in a global economy.

1 Introduction

The efficiency of performance of the electric motors is considered one of most important indicators in order to make decisions for the re-conversion technology of a productive process, where the total cost of production have a great influence on the productivity and competitiveness of a company in a global economy.

However, taking a technological approach, the motor is only one of the components of the production process where are participating several devices in each step of the production, consequently although the motor has an important part of energy consume, it has no so much importance respect the total cost of the production, highly likely the efficiency indicator is not enough decisions-taking steps in modern strategically management.

Thus a more integral approach needs indicators of technological and innovation management starting from motor selection up-to running the motor within the productive process, in such a way that you can use innovation opportunities present in re-conversion process itself, and can help in large degree to pinpoint the production indicators.
2 A New Approach in Motor Management

Management of electric motors in a productive process requires both of technological management indicators and innovation management including from equipment selection up-to adaptation of it from the process point of view, in such a way that advantage can be taken from industrial re-conversion carried out, giving a mayor contribution in productivity.

This new process approach differs from what was traditionally done before, when equipment was changed as function of technical requirements and energetic indicators, normally incorporated in process of technology “ready-to-use” without any kind of training or better skill means.

Taking into account technological management and process approach, allows to obtain a better acknowledgement and new skills at all organization levels, this way when the technology changes we are able to identify improvements in the processes which bring an increase in productivity and competitiveness.

3 Technological Management

Technological management include administration and management of selection and evaluation processes, technologies gain, follow-up and adaptation, handling of information, and mainly, management of one of the most important sources in competitiveness: innovation.

In order to bring into a production line elements of a re-conversion project, where the motor is the piece of equipment with a largest energy use, it is compulsory to look into three key aspects of technological management; technology segregation and characterization, defining indicators and finally, preparing opinion structures for re-conversion and changes aiming in the productivity.

3.1 Segregation and Technological Characterization

Production segregation processes and characterization, is one of the management tool which allows us to identify how strategically important the motor is within the process different stages and its role in production costs and impact in the innovation created by the changes or improvements, due to incorporating efficient technology.

Segregation consisting in the description of all activities, processes and stages required for production, including raw materials up to the finished product, using technical flow charts, in order to pinpoint core and peripheral technology of a process and its categories, this is, if they are “hard” (inside acknowledgement of equipment and processes, hardware) or “soft” (such as method, software) taking into account not only energy variables but production variables as well.
As a result of segregation we obtain a chart depicting functions and stages together making clear the main technologies that due to its importance in the process, defining technical parameter of the finished product.

Identifying and classifying processes, characterization of final use equipments, operating conditions and its production function, are factors to develop as management elements during the diagnostic stage, in order to help the energy appraisement board.

Process is defined as a serie of activities in systematic following sequency, that transform raw material into results, of specific characteristics with an added value.

Following aspects concerning electric motors, must be taken into consideration in different processes of a production system for its characterization:

- Identify different processes and production function that the motor metes in each one of them and draw a operating flow-chart with collected and analysed information.
- Identify and describe operating conditions concerning production variables of the different stages of the company.
- Identify organization and management processes involved with strategically planning and specifically with follow-ups of production lines, maintenance, purchase policy and acquiring of technologies and skill training.
- Finally, clearly identify the relation of the motor with production in the different stages and its impact in the final cost of the product and final tag price in the market.

3.2 Elaboration of Indicators for Integral Management

In this area we must consider measuring different parameters, both electric as web as technologic and of production, aiming to the next:

- Asses performance of the motor and process looking for productivity and improvement goals.
- Asses the cost of increasing efficiency and confidence of the system considering final costs and broadly speaking the productivity.
- To set goals and levels of involvement.
- Asses technology trends
- Identify problems in operation, maintenance and re-conversion.
- Identify innovation opportunities
- Asses impact on final costs

Broadly speaking, indicators should be measurable in terms of degree or frequency, should have a significance in order to recognize and consequently, a description. Last but not least it must be able to control.
3.3 Indicators for Selection and Assess of Technological Alternatives.

It is fundamental the right assessment of the energy and technical needs with aims to productivity, conforming to indicators and saving goals or efficiency for the sake of it, in other words, increasings in raw material that reflect in production increasing also.

For technical alternatives selection, it is a must the results of the energy and technical appraisement board that allow to point out technical specs of equipments and process to improve.

As a result of this stage, it is hoped to have enough acknowledgement for the selection and location of suppliers with a large acknowledgement and handling of the technology and its use in the production process, since not everyone selling technology is able to put it into practice and carry-out its maintenance.

Among indicators for selection of alternative technologies close to motors, we must bring into consideration:

- Motor power selection.
- Savings assess in reduction of loads.
- Savings assess if using electronic speed controllers.
- Assess profits improving electrical energy quality.
- Assess the cost in increasing confidence in the system.
- Assess planning characteristic of suppliers companies (it is recommended they have an ISO 9000 certificate)

4 Technological Follow-Up

Technological follow-up allow us to establish tools for keeping abreast with the new technologies, identify in advance the future in technology in order to forecast changes in the market and technology trends. Technological follow-up must identify the capacity for changes to the company, as well as to compare the best in permanents benchmarking; and establish future visual forecasts allowing to take action in the present, one step ahead of the changes and break-downs.

5 Energy Saver Motor

Use of motors of high efficiency, is one of the elements for energetic improving within a process in which there are items overdue to technical re-conversion in a production line, where induction motors normally take the largest toll in electricity consuming.

High efficiency motors came in production in the mid 70’s by some USA companies and its use started rather slowly. It could be said that main factor in the increasing use of these motors was due to high electricity rates policy, as a direct consequence of oil
price rise, bringing an increment of the order of 12% annually during several years. Since 1997 it is compulsory the use of high efficiency motors in USA, Canada and Mexico.

However, the scarce technical information dealing with technologies of energy efficiency, have made that its use is seen as the only step to take when reducing energy costs. This has presented technical inconveniences in production processes when motors of high efficiency have been used, without a previous technical asses related with the production process.

Use of these motors is recommended in the following cases:

5.1 **Selection of a Motor for New Installations or as Replace of a Motor overdue for change.**

In this case it is important to consider, in the first place, if the motor meets loads and specs of the system, among them, momentum characteristics, start current, starting time, etc.

Met loads and electric specs, a next step is to asses economical turn-out of paying an extra money for the high efficiency motor.

Appraisements conducted say that it is recommended to study the possibility to purchase a high efficiency motor in the following cases:

- In motors from 10 HP to 75 HP, when running for 2500 hours or more at year.
- In motors with lower power (small and large) when running for 4500 hours or more.
- When used together with Variable Frequency Drives to operate pumps and fans (savings up to 50% can be obtained).

5.2 **Repair or Replace**

When a motor fails three solutions are present: repair the broken-down motor, to purchase a normal new one or a new high efficiency one.

In deciding if to replace the broken motor for a high efficiency one, it must be taken into consideration:

- Motors of less than 40 HP and more of 20 years of use are good candidates to be replaced, as well as the 7.5 HP no matter how old they are.
- If costs for new winding go above 50% of price for a new one, it is recommended to replace for a high efficiency motor.
5.3 Replace of Oversized Motors

Good practice shows that normally it is economical interesting to replace the motor with a load level under the nominal for a high efficiency one, and sometimes, with motors of normal efficiency. Subsequent to and notwithstanding, it is important to work out the efficiency of the motor in operation before replacing take place.

For everyone of the former cases, besides the technical and economical parameters involved, it is important to take into account the management indicators, together with the tools of follow-up and segregation, in order to obtain a better impact in production.

6 Conclusion

In the current competitive theatres, the induction motor, due to its importance in the production processes, demands a more integral management, able to produce a larger impact in production, not only for improving the energy efficiency, but also for technological innovation opportunities, that will be supported by the management, with emphasis in the segregation and technological follow-up.

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Quispe, Enrique: Una Visión Integral para el URE en la Aplicación de los Motores Eléctricos de Inducción. Revista El Hombre y La Maquina Año XV No.20-21, Jul/Dic 2003, Colombia, p.52-59


Condition Monitoring to Maintain Motor Efficiency and Dramatically Reduce Unplanned Motor Outages

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Abstract

Unplanned plant outages not only cause industry losses from lost output, but there are also considerable energy costs associated with these events. Condition Monitoring (CM) of key plant is therefore important in order to take actions to avoid minor problems developing into major faults, many of these problems which themselves have associated energy losses. In recognition of this potential for energy saving, Future Energy Solutions is active in the promotion of maintenance best practice as a way to achieve energy savings “through the back door”.

This paper summarises some of the key techniques that are appropriate for monitoring the condition of motors, allowing motors to be repaired before they fail completely. Finally, the many linkages between energy efficiency and maintenance best practice have been described, and the benefits of combining some of these activities.

1 The Costs of Failure

The cost of unplanned outages explains why there is so much management interest in reducing the risk of plant failure, and hence the attention given to effective maintenance (Falkner & Tutterow, 2002). Table 1 shows the typical costs of unplanned outages in a variety of industries.

Energy can represent a significant part of these costs, and can be hidden in many ways, as shown in Table 2.

Table 1: The costs of unplanned downtime (European Copper Institute, 2001)

<table>
<thead>
<tr>
<th>Industry</th>
<th>Typical financial loss per outage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Computer centre</td>
<td>Euros 750,000 per event</td>
</tr>
<tr>
<td>Financial trading</td>
<td>Euros 6,000,000 per hour</td>
</tr>
<tr>
<td>Glass industry</td>
<td>Euros 250,000 per event</td>
</tr>
<tr>
<td>Semiconductor production</td>
<td>Euros 3,800,000 per event</td>
</tr>
<tr>
<td>Steel works</td>
<td>Euros 350,000 per event</td>
</tr>
</tbody>
</table>
Table 2: The energy costs of unplanned plant outages

<table>
<thead>
<tr>
<th>Affect of unplanned breakdown</th>
<th>Related energy cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temporary reduction of output during breakdowns</td>
<td>Core or background energy needed to maintain essential services is spread across less product, and so the specific energy consumption rises.</td>
</tr>
<tr>
<td>Start up losses</td>
<td>A lot of energy is lost during the warm up time of high temperature processes</td>
</tr>
<tr>
<td>Alternative methods for re-gaining production used</td>
<td>Less efficient methods of production may be used, perhaps using older equipment or involving additional transport costs</td>
</tr>
<tr>
<td>Loss of product during warm up time</td>
<td>Some processes have to produce scrapped product while they are “warming up”.</td>
</tr>
<tr>
<td>Energy used in part processing the product is lost</td>
<td>Much energy may have been expended in getting a product to near the end of a production process, and this energy will be wasted.</td>
</tr>
<tr>
<td>Disposal of damaged product</td>
<td>There may be energy costs involved in the physical disposal of scrap product.</td>
</tr>
<tr>
<td>Emergency repairs made to re-start plant asap</td>
<td>Maintenance staff will do what ever is quickest to get the plant running, with speed taking priority over getting the optimum quality repair or looking for the most efficient spare part or replacement kit.</td>
</tr>
<tr>
<td>Rework costs</td>
<td>Additional energy used in re-working spoiled product.</td>
</tr>
<tr>
<td>Time lost for less urgent work</td>
<td>Time that could have been spent on energy saving work is lost</td>
</tr>
</tbody>
</table>

2 Designing an appropriate condition monitoring regime

Regular monitoring of all motors using a comprehensive combination of condition monitoring techniques will give the best warning of developing problems, but such an approach would be very costly. Instead it is most cost effective if a company creates a CM plan that matched their particular needs, based on the criticality of the motor and the likely reasons for failure. Examples of the questions to ask in order to understand what is most appropriate for a particular motor are:

What would be the affect on production if it failed? This is mainly lost product and the cost of idling time both while the motor is being replaced or repaired, and during the subsequent process start-up.

How long will it take to get production re-started if it fails? Is a spare kept in a company inventory, is it a regular stock item at a local distributor, or is it a long lead time item from the manufacturer? Is your motor repairer able to repair it, and how long will this take?

Is there system redundancy? Multiple pump or air compressor systems routinely have a spare unit to allow for production to continue as normal while one unit is down for maintenance.
What are the likely failure modes?

- How frequently has it needed repairing?
- Does it tend to fail for the same reason?
- Is there anything unusual about its duty or location?
- Are there existing CM records that give any useful information?

By understanding the most likely reasons for motor failure, you can select the techniques that are the most appropriate for each motor. If you do not have maintenance records with this information, plant operatives or your motor repairers may have useful anecdotal information.

3 Condition Monitoring techniques for motors

There are many different CM techniques suitable for use on motors, but this paper just considers three of the most useful but possibly unfamiliar; thermography, vibration analysis and Motor Current Signature Analysis. Experienced plant operators can tell a lot about the condition of a motor by the sound it is making and from feeling the temperature and vibration. But by using specialist CM equipment it is possible to pick up problems at an earlier stage, and also to plan future maintenance activity by trending deterioration over time.

Insulation testing is also a standard technique for any critical electrical equipment to gain advance notice of winding failure. Information on this is widely available from equipment suppliers, and so is not further described here. Checks on the local power quality (waveform distortion, line voltage or phase imbalance) are also important in avoiding problems developing in the first place.

CM Techniques – Thermography

Modern thermographic cameras give a quick and easy way to rapidly assess motors for unusual temperature rises. It is useful not only for quickly checking the overall running temperature of lots of motors, but also for tell tale local “hotspots” that can help to identify particular faults.

Bearing over-heating

This can be due to several causes, all of which represent addition energy losses:

- Over lubrication
- Inadequate lubrication
- Contaminated grease
- Angular misalignment
- Parallel misalignment
- Excess drive belt tension
- Excess axial thrust
- Loose fitting bearings
- Leakage current
- Weak motor foundation or “soft foot”
- Excess load.

Figure 1: Thermal image of an over-heating drive end motor bearing

**Winding failure**

If interwinding insulation fails, the motor is likely to keep running, but local heating will probably show on the motor frame, (figure 2).

Figure 2: Thermal image of a motor with failed interwinding insulation
Over-heating

The motor cooling system is designed to dissipate all the losses under normal conditions, but if the load or ambient temperature is excessive, then the frame will over-heat. If a thermographic camera is not available, then a thermometer can be used to measure the frame temperature, ideally using the lifting hook socket in order to get a good thermal contact with the frame. Non-contact infra-red spot thermometers are particularly useful for looking at the drive end bearings, where access while the motor is running may be restricted. The much greater speed of response compared to thermometers that rely on direct contact is a big benefit when looking for local hotspots.

If the rotor on a failed motor is equally dis-coloured at both ends, then this is an indicator of general over-heating rather than from a specific part of the motor failing.

CM Techniques – Motor Current Sensing Analysis (MCSA)

MCSA is a very sensitive technique that uses the stator to sense anomalies in the electromagnetic flux in the airgap between the stator and rotor. These can be caused by slight non-concentricities of the rotor:shaft assembly, or very small changes in the stator or rotor fields. It is particularly good at detecting the following problems, all of which have energy efficiency implications:

- Broken rotor bars
- Winding insulation degradation
- Eccentric rotor
- Bent shaft
- Oscillating load.

The actual equipment is easy to use, only requiring a current transducer to be fitted to any one of the supply cables. Since the accuracy is dependent on the strength of the magnetic field, best results are achieved with the motors running at or near to full load.

The resulting signal is an accurate indication of the magnetic field, which is then displayed in the frequency domain, as in figure 3. What is looked for is the relative magnitude of particular frequency sidebands around the fundamental supply frequency. For instance, rotor bar problems are identified by peaks at the actual rotor frequency, (this is very close to the supply frequency, differing just by the slip). Problems with the windings show as peaks much further from the supply frequency, and their frequency (and amplitude) will also vary with load. While a very powerful and sensitive tool, some experience is needed to precisely identify the indicated fault.

Detection of Broken Rotor Bars

MCSA is unique in being able to detect faulty rotor bars. Although vibration monitoring can also identify failed rotor bars, by the time this technique detects a problem, the damage is likely to be far more advanced.
Functionally a damaged rotor will mean that the motor has reduced output torque, which may not be noticed or matter until times of high load, when additional stress will be put on the other rotor bars. The failure can either be a failed end connection in a fabricated cage, or porosity in a cast cage. In some larger designs with rotors embedded on the outside of the core, part of the rotor can become detached, which can cause severe damage to the motor.

There are two principle reasons for rotor failure:

- Frequent direct on line starting, which causes thermal and mechanical shocks to the rotor. The number of starts before damage might occur depends primarily on the size of the motor, but also on the speed and inertia of the load.

- Pulsating loads such as reciprocating compressors or coal crushers, where torque pulsations cause additional stress on the rotor bars.

![Figure 3: A MCSA display of a good motor (left), showing just the fundamental stator flux (at the mains frequency). The second plot (right) shows the MCSA of the same motor but with damaged rotor bars, showing the additional peaks at the actual rotor frequency.](image-url)

**CM Techniques – Vibration Analysis**

There are many types of vibration analysis suitable for monitoring motors, with the fast fourier transform analysis best illustrating the capabilities of this technique. By relating the frequency of the vibration to the characteristic signature of each mode of failure, Vibration Monitoring Analysis allows users to actually identify the cause of the problem. This is a very powerful diagnostic tool, with the characteristic frequency of common faults shown in figure 4. Hand held probes are lower cost and so more popular, but only give a single reading of the total vibration level. This means that while they give an indication that there is a problem with the motor, they will not indicate the cause of the problem. In particular, because of the limited frequency response, they will not detect the characteristic high frequencies indicative of bearing failure until a very advanced stage.
## Typical Fault & Dominant Frequency Table

<table>
<thead>
<tr>
<th>Fault Type</th>
<th>Details</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>IMBALANCE</strong></td>
<td>$x \ 1$</td>
<td>Imbalance occurs at rotational frequency equal to $1 \times$ rpm of the out of balance part. Usually radial (horizontal or vertical). Sometimes dynamic (axial). Amplitude is direct indication of degree of imbalance.</td>
</tr>
<tr>
<td><strong>MISALIGNMENT</strong></td>
<td>$x \ 2$</td>
<td>Typically angular and/or offset problems in couplings. In both radial and axial directions also apparent at $1 \times$ rpm because of imbalance inherent to misalignment.</td>
</tr>
<tr>
<td><strong>LOOSENESS</strong></td>
<td>$x \ 2 \quad X \ 1$</td>
<td>Mechanical - caused by loose rotating parts or excessive play in machine mountings. Typically a machine will vibrate as it hits a natural resonant frequency during run up or run down - once the associated rpm is passed vibration amplitude decreases.</td>
</tr>
<tr>
<td><strong>PASSING</strong></td>
<td>$X \ 1$ and $(x1)$(No of blades/vanes)</td>
<td>Usually cause a $x \ 1$ frequency component and a multiple related to the number of vanes/blades. Also referred to as blade pass frequency.</td>
</tr>
<tr>
<td><strong>MESHING</strong></td>
<td>No. of teeth $\times$ rotational frequency of associated gear</td>
<td>Defects cause low amplitude high frequency vibration and show imbalance, misalignment and tooth damage associated with Gear Mesh Frequencies. Gear Mesh Frequency = output gear rpm $\times$ No. teeth in output gear. e.g. 32 tooth gear operating at 300 rpm ($300/60 = 5$Hz) GMF = $32 \times 5 = 160$Hz.</td>
</tr>
<tr>
<td><strong>BELTS</strong></td>
<td>Related to rotational speed and multiples of rotational speed</td>
<td>Vibration analysis will identify rubbing and misalignment. Use strobe techniques to identify slipping belts.</td>
</tr>
<tr>
<td><strong>ELECTRICAL</strong></td>
<td>At supply frequency and multiple of $50$Hz(UK)</td>
<td>Vibration will stop when power is turned off!</td>
</tr>
<tr>
<td><strong>BEARINGS</strong></td>
<td>$3-10 \times$ rpm &amp; Higher</td>
<td>Bearings indicate problems at high frequency $2-60$KHz (in the early stages of deterioration) and at low amplitude. Range of techniques available with bearing capability.</td>
</tr>
</tbody>
</table>

Figure 4: Common sources of motor vibration and their diagnostic frequencies.

## 4 Integrating Condition Monitoring into a Motor Management Policy

When a motor is taken out of service, either as a result of unplanned failure or planned maintenance, then it is a good opportunity to consider replacing with a new motor with a higher efficiency, hence saving energy. Many companies do indeed have a written policy on buying Eff1 motors, and only accepting quality rewinds, (Blandford, 1999 and Action Energy, 1999). However, because most motors fail at an unpredictable time, the imperative to get equipment running as soon as possible means that the policy is
often over-ridden. By giving advanced notice of when motors are taken out of service, Condition Monitoring (CM) can be a big help in making such a policy work in several ways:

- A move to planned rather than rushed motor repairs, ensuring that there is time to do a quality job, and that the correct parts are in stock.
- Regular CM measurements can highlight items for attention during servicing that may not have been picked up by a repairer when a motor is out of service.
- New motors can be ordered to replace motors before they finally fail, over-coming the problem of motors that are known to be poor being repaired because it is quicker.
- A reduced on site inventory can be kept, meaning that the latest motor designs are used. This also reduces the risk of early failure due to false brinelling while in storage.
- CM inspection as part of the installation process can highlight faulty repairs.
- A knowledge of the motor duty obtained while it is working can sometimes point to the need for a smaller or larger motor when the time comes for replacement. It is too late to take measurements once it has failed.

5 Conclusions

Unplanned plant outages not only cause industry losses from lost output, but there are also considerable energy costs associated with these events. Condition Monitoring of key plant is therefore important in order to take actions to avoid problems developing into something more serious. This paper reviews some of the less well known techniques for monitoring the condition of motors, which taken together can detect most common problems, allowing motors to be repaired before they fail completely. Finally, the many linkages between energy efficiency and maintenance best practice have been described, and the benefits of combining some of these activities.

References

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Energy Saving Strategies for Electric Motor Based Appliances

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Abstract

The role of electric motors and actuators in a domestic environment is explored, by reviewing the more common solutions adopted and by suggesting possible innovation aimed at increasing the energy saving, while maintaining the specifications of the appliances market. A significant contribution in this direction is obtained from a large use of electric drives, instead of simple electric motors, which also means to take advantage from the supply flexibility offered by static converters and from the intelligent algorithms that allow for variable speed at high efficiency. Thanks to more sophisticated algorithms, able to reconstruct important variables with little or no physical sensors, AC machines seem taking over DC or universal motors, and also the integration technology favors more compact and efficient devices. A non secondary impulse is also given by home and building automation technology, that uses system communication and status knowledge sharing to optimize the overall system performance.

1 Introduction

A general overview of the civil area energy consumption and expectation (residential and service) can be found in the Italian Third National Communication under the Framework Convention on Climate Change as summarized in Table 1 (Ministero dell’Ambiente, 2002). The amount of electricity used for the residential uses has increased, in the last decades, in line with the economic growth of the European countries and a global amount of $5 \times 10^{15}$ BTU, i.e. 43% total energy consumption in residential sector, is estimated for the appliances contribution. On the other hand the domestic appliance industry acknowledges the relevant environmental impact of household components during their total life cycle and consents to reduce it with technological upgrading. Within this global trend the basic electro-mechanical concept of a motor has evolved to an electronically controlled machine drive with both sophisticated sensors (hardware or software based) and high-performance motors. The Home automation in turn can assist the consumer, so that its behavior is more compliant in terms of energy saving, rationalization of the energetic consumptions, monitoring and optimization of energy resources at home.

The paper is thus investigating all the strategies useful to this aim; special attention is paid to the application power electronics (static converters), the use of digital algorithms to perform variable speed operations, and the intelligent coordination of appliances and other domestic devices within an home and building automation environment, where a non secondary role is played by power and energy metering.
Table 1: Energy demand: trend scenario

<table>
<thead>
<tr>
<th></th>
<th>Renewables</th>
<th>Coal</th>
<th>Gas</th>
<th>Oil</th>
<th>Electric energy</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>2000 (Mtoe)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Civil Sector</td>
<td>1.16</td>
<td>0.07</td>
<td>20.07</td>
<td>7.19</td>
<td>10.59</td>
<td>39.71</td>
</tr>
<tr>
<td>Total</td>
<td>12.91</td>
<td>12.88</td>
<td>58.37</td>
<td>91.29</td>
<td>66.56</td>
<td>185.21</td>
</tr>
<tr>
<td><strong>2010 (Mtoe)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Civil Sector</td>
<td>1.07</td>
<td>0.00</td>
<td>27.57</td>
<td>2.90</td>
<td>11.05</td>
<td>42.59</td>
</tr>
<tr>
<td>Total</td>
<td>13.24</td>
<td>14.71</td>
<td>76.82</td>
<td>87.71</td>
<td>71.47</td>
<td>200.29</td>
</tr>
<tr>
<td><strong>2020 (Mtoe)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Civil Sector</td>
<td>0.92</td>
<td>0.00</td>
<td>31.24</td>
<td>1.19</td>
<td>13.16</td>
<td>46.51</td>
</tr>
<tr>
<td>Total</td>
<td>13.00</td>
<td>14.70</td>
<td>96.75</td>
<td>96.37</td>
<td>87.34</td>
<td>228.00</td>
</tr>
</tbody>
</table>

2 Electrical devices evolution for appliances

The automation for domestic energy management requires such components as converters, electrical motors and actuators, sensors and communication devices. Their choice in itself is a first relevant factor in energy saving, as a consequence of their specific consumption performance (actuators), or their functionality (sensors, interfaces, communication nodes). About two and a half billions motors and actuators rated lower or much lower than 1 kW are in use worldwide; in North America, single and multi-pole/multi-speed single phase induction motors are used to provide mechanical action in more than 90% of major appliances. Control devices are centrifugal switches, pole change switches, PTC devices, mechanical transmission, Triac on/off and Triac based phase control. Universal motors are used primarily in small appliances, still today controlled by a mechanical governor attached to an on/off mechanical switch. Their efficiency ranges from 15% to 85%; notice that 1% increase in efficiency would amount at a 1.7 billions kWh/year incremental energy saving (Moreira 2003). A major possibility for improving appliances performance is thus available, by introducing new regulation techniques based on power electronics devices. Their diffusion is however still limited by at least three reasons: i) cost increment; ii) manufacturers doubts on the new techniques reliability; iii) manufacturers doubts on the new devices durability. A possible ground for this misunderstanding is that design criteria for electronic static converter and drives are mostly based on industrial requirements somewhat different from domestic applications, where for example low power, low cost, limited control performance, high reliability and durability are items of primary concern.

2.1 Motors and actuators for appliances: a review

Motors employed for domestic appliances can be classified as primary devices (e.g. elevators, refrigerator compressors, washing machines), or low-power auxiliary components for the appliance operation (e.g. relays or servomotors for power line opening/closing, lighting orienting, small power actuators). The energy impact of the latter is
marginal; however the former category, which is mainly responsible for energy consumption, deserves closer consideration and is the primary topic of this paper.

Motors for domestic appliances come in a great variety of construction types, probably even more than in industrial environment (Multon et al. 2000), with the aim at reducing cost and space occupation, while still satisfying to the speed and torque requirements (steady state operation, starting, standstill, reasonable level of ripple), without special attention devoted to energy items in terms of efficiency or power factor (single-phase actuators, with their different varieties including universal motors). However, even for them the quality improvements allowed by speed regulation and static converters, have suggested a number of novel solutions. A significant example is the compressor set for climate conditioning, that in a standard home can require up to 20% of the total energy consumption. The motor, exposed to a cooling fluid at high pressure and temperature, guarantees high reliability so that usual solutions with induction motors, are more and more replaced by systems employing synchronous machines (Murakami et al. 1999).

2.1.1 Induction motors

Speed regulation of induction machines is usually performed in industry by frequency regulation, which requires a static inverter, often more expensive than the regulated motors; due to this reason appliances manufacturers prefer non-optimal, lower cost techniques, such as static voltage regulator at fixed frequency (e.g. for blowers). This solution can be adopted for all motor types: split-phase, with capacitor, or shaded pole. For capacitor-run motors, a parallel connected modulating triac allows the tuning of an optimal capacity value according to the load, by finding the best compromise between starting torque and efficiency at the rated speed. Low-cost converter are also obtained by using a single leg inverter.

2.1.2 Commutator machines

This is the preferred solutions for dc voltage and/or low voltage source, which is also available with ac voltage for high speed without converter, i.e. the well known Universal motor able to reach up to 50000 rev/min, even though brushes and commutator wearing, together with mechanical vibration and dust intrusion, shorten the life cycle to a few thousands hours. The main advantage of dc motors is the easy regulation through simple converters like the single-switch chopper, when the motion reversal is not required. Universal motors, together with mechanical reduction gears (e.g. for portable drills), allow for a good compactness; with the use of voltage regulators they can also be employed for such applications as washing machines or extractors, where previously capacitor induction motors have been preferred. When fed by a triac based rectifier or low frequency chopper, it can improve the performance by reducing the volume, so compensating for the cost of electronic components, by also reducing the noise.
2.1.3 Synchronous machines

For driving pumps up to 100 W (washing machines) a typical application is a 2 pole synchronous motor, single-phase fed at fixed-frequency, with permanent magnet rotor (ferrite), and with an U-shaped stator and air-gap dissymmetry. The advantages are reduced cost and volume; a recent execution with a cylindrical shaped stator is able to significantly reduce the torque ripple (Ostovic, 2002). An alternative solution are self-commutated drives. Usually a salient pole structure is preferred for the armature, as the winding can be more easily manufactured; for an external rotor, the armature construction is the same as for the internal one, to maintain the same construction technique. The phase number is kept as low as possible, even if this increases the torque ripple; the supply is realized by current pulses (easier solution) and the commutation is triggered by Hall effect transducer. For blowers based on brushless motors, operating in a one-way direction, the rotor is made in plastic ferrite. The supply is single phased, with a bifilar winding fed from a two-transistor inverter, integrated with the transducer in a single printed circuit, serving also as the armature support. When starting, the non-zero alignment torque gives the initial position. The external rotor, integrated with the blower turbine, has an inherent high inertia that reduces the torque ripple; better performance at higher cost can be obtained with three phase, more complex solutions.

2.1.4 Variable reluctance motors

These are quite simple and robust machines, only affected by relevant noise: a widespread use is for electric razors, where the ac supply frequency produces a double frequency magnetic force, generating the resonant mechanical vibration. The reluctance brushless motor can serve as a good substitute for dc motors in a number of important applications, where a static inverter producing a unidirectional current, is required. The three-phase version can operate in bi-directional way, being useful for drills, washers etc. Even for high speed extractors or vacuum cleaners they can compete with universal motors, by overcoming the noise problem with an asymmetric stator and bi-phase execution. The converter has a simple layout, with two transistors, each magnetizing a phase; the demagnetization is obtained with a small chopper returning the unused energy to the supply. A power factor correction can also be achieved.

2.2 Novel solutions.

A key for innovation in energy savings for appliances is to carefully adapt a number of relevant solutions already tested and in use in the industrial sector, where a large use of static converters and digital control has transformed standard motors fed from a fixed supply grid into electrical drives fed from flexible energy sources with variable frequency and voltage, intelligent enough to fit application requirements. It has already been mentioned that some new criteria, like low cost, low to medium performance, durability and reliability, will differentiate their design with respect to the industrial solutions. This can be obtained by reducing the component number for a single solution, and drastically eliminating sensors or extra devices. A few examples will follow.
2.2.1 Future Energy Challenge I-drive

In 2003 the Future Energy Challenge (http://www.energychallenge.org/2003FEC.htm) proposed as a theme "Energy Challenge in the Home". Target hardware costs were US $40 for a combination motor and motor controller on the basis of 1 million units/year. It has to be able to operate from a single-phase residential source, deliver rated shaft load of 3/4 HP (or 500 W) at 1500 RPM, exhibit a useful speed control range from 150 to 5000 RPM, besides, it has to provide power efficiency of at least 70% for loads ranging from 50 W to 500 W at a specified speed and power factor more than 0.8, with a 10 years durability. One solution, called I-drive deserves a mention and some comment. The drive scheme, based on a single phase induction motor, is reported in figure 1, and the final goal was reached by operating on any single block (Wells et al. 2004).

**Rectifier. Power Factor Correction (PFC).** A classical rectifier provides a maximum power factor of 0.8 and power factors less than 0.7 were observed in hardware. An improvement can be obtained by using an active PFC Boost Circuit, bringing the PF at more than 0.9.

**Inverter. Cost reduction with integrated circuit (IC).** An IC including gate pulses generation and dead time management can consistently decrease the inverter cost. It also improves the reliability by increasing the MTBF; the inverter has a low modulation frequency which reduces the losses and the required performance of the cooler.

**Motor. Efficiency optimization.** The machine design is based on a low slip operation due to the variable speed control and the large inrush current at starting can be so disregarded. The obtained efficiency is reported in figure 2.

**Harmonics reduction.** A proposed solution, with a proper implementation of voltage waveforms, allows to reduce a consistent harmonics number, by limiting the commutating frequency at $f_{\text{comm}} = (2n+1) \times f_{\text{out}}$, where $n$ is the number of cancelled harmonics.

**Other tricks and evaluations.** The converter is mounted on the motor end, thus exploiting its cooling fan. The cost has been calculated on the basis of market quotation and the 1 million unit basis reduces it consistently at the required US $40. The durability has been evaluated and results within the 10 years requirements.

2.2.2 Integrated converter

Recent technology advances allow for a complete integration of the power converter and the regulator, including the PFC, in a compact module. This is the case with the solution shown in figure 3, implemented in an Intelligent Power Module (IPM), where the regulation strategy guarantees for a minimum current distortion, high PF, at low cost. The PF reduction is obtained with no separate circuit, but properly conveying, by the control sequence, free energy back to the DC bus (Consoli et al. 2004).
2.2.3 Field Oriented Control induction motor drive

Field Oriented Control (FOC) is a sophisticated, high cost regulation technique for induction machines, usually employed for high budget plants or when very high performance is required; therefore its use seems not proper for common appliances. Nonetheless due to advances in microprocessor features, even complex algorithms can be made transparent within a system of fully integrated components, at a reasonable cost, to be covered with a consistent number of pieces manufactured per unit. On this basis a FOC-based induction motor drive for washing machines has been developed. The adopted solutions to reduce the cost while still keeping true FOC performances, are: one single IC including a low cost DSP which executes most of the calculation and interface functions; use of two low cost current shunts, instead of Hall effect sensors; a speed control loop only for medium to high speed, excluding the more questionable low speed range, where an open loop solution is adopted. The extra cost is compensated by higher performance and more available functions, with a cost reduction in the me-
2.2.4 A reluctance motor with a single switch.

Beyond a number of advantages in the use of a reluctance motor (see above), a solution proposes a further reduction in the converter cost, by adopting a single active switch, as seen in Fig. 4, fed by a single-phase or three-phase grid. Q1 is the main active switch; other elements required are diodes D1 and D2, and an electrolytic capacitor of a much lower capacity (100 to 200 times) than the main capacitor C1. The starting sequence (see Fig. 5) and operation on four quadrants are permitted thanks to a sophisticated software program (Krishnan et al. 2004).

3 Home automation for energy saving

Home and building automation are key technologies for introducing intelligence in a residential environment. Energy saving is one of the more popular demands that can be addressed by this technology.

3.1 Electric Energy Measurements

As the electric energy consumption (kWh) in a household is constantly increasing, the need for measuring high current is no longer limited to industrial applications (Koon 2002). In addition the growing complexity of household electrical equipment generates higher levels of harmonics that should be accounted for in the measurements (Moulin 2003, Calegari, 2005). Indeed, non-linear loads such as home entertainment equipment, high efficiency lights, desktop computers, adjustable speed drives etc., are sources of harmonic load currents in low voltage installations, which are responsible for
the distortion of the line voltage, leading to harmonics on the load input voltage (on linear-loads also). Hence, the ability to measure the harmonic power is as critical as the traditional accuracy performances used to classify energy meters (Calegari, 2005). In residential single-phase networks, the power and energy measurements through a low-cost electronic solid-state digital meter, for the nonsinusoidal case, requires an optimised signal acquisition system (e.g. for I and V). Otherwise, noticeable errors (10% also) are introduced. Furthermore, the low-cost implementation of some theoretical power definitions is difficult, and these can be only approximated. About the general architecture, among proposed different implementations, the Energy Meter IC-based architecture is more flexible and more proper to integration inside the communication technologies for the home automation. It allows the use of a simple, low cost 8-bit MCU (Microprocessor Control Unit) for the management and communication tasks. This may be integrated inside the node of the fieldbus network used for the AMR (Automatic Meter Reading) or AMM (Automated Meter Management) service. The current sensor and the design of the PSU (Power Supply Unit) needs particular care. In some filed-buses the PSU for the measurement circuits can be provided by the host network node, and this simplifies or avoids entirely the design of the PSU.

As for the relation with power factor (PF), in nonsinusoidal case, if \( P = P_1 \) and \( V = V_1 \) (sinusoidal voltage source), PF (Grady et al. 1993) is:

\[
PF = \frac{P_1}{\sqrt{V_1^2 I_1^2}} = \cos \varphi_1 = \cos \varphi_1 - \frac{1}{\left(1 + \left(\frac{THD_1}{100}\right)^2\right)}
\]

where THD is the Total Harmonic Distortion % for the current. Single-phase power electronic loads tend to have high current distortion. Therefore, their true PF are generally less than 0.707, even though their displacement PF \( (\cos \varphi_1) \) are near unity. In general, it is needs to compensate for poor distortion PF. As for the relationship between power factor PF and reactive power \( Q \) in a nonsinusoidal system, it depends on the definition adopted for the reactive power \( Q \). Hence, in general (Filipsky et al. 1994), compensation of the reactive power \( Q \) alone may be useless for PF improvement.

### 3.2 Automatic load management

The load control and rationalization of power consumption in a household bring advantages to both the user and the energy supplier. In fact it is possible to reduce the inconvenience due to the accidental power shortage, due to the intervention of devices limiting the maximum allowed power (contractual power); which is specially true for such countries as Italy where the lack of energy self-sustainability determines policies intended to limit the residential consumption, in favor of the industry requirements.

It has been evaluated that a typical distribution of power requirements for a household would amount at 13 kW for a simultaneous use of appliances (even this is far from likely); on the other hand a typical power contract is limited to 3 kW or 4.5 kW, which implies a very careful use of appliances, possibly distributed during the whole day.
span, or even in preferred part of the day or of the week (e.g. night or weekend) to take advantage of favorable rates. In Fig. 6 an household appliances distribution is shown where a communication among appliances is provided by a bus system (here a power line, so that the communication share the power line).

Most appliances (energy relevant) are connected to the bus by a node. Other appliances are not endowed with specific intelligence: in this case it is possible to control them by using “intelligent” sockets, also connected to the bus. A power meter detect the whole power in use.

In a centralized load management, a supervising unit operates i) by reading the input energy meter, it monitors the total absorbed power in any instant, and compares it with the maximum allowed value; ii) on this basis it authorizes the connection of the intelligent appliances, according to a priority table, determined on a rational basis and user preferences, so that the limit is not exceeded; iii) it also plans the absorption of all appliances within a 24 hour span, as far as this is allowed by other higher priority criteria or user requirements; iv) when the total power is expected to exceed the limit value, it automatically disconnect the appliances, starting with the lower priorities.

Even if this procedure is quite common, still some disadvantages can be singled out, due to a quite rigid priority list. Consider for example the case when the supervisor is going to disconnect a washing machine during the water heating phase; as a consequence the stored thermal energy is definitely wasted. On the contrary it would be a wiser solution to keep the machine drum rotating (only about 0.1 kW), while disconnecting the heating resistor (about 2 kW). For a distributed intelligence load management (Fig. 7) there is no a supervising unit; on the other hand the decision is taken by the intelligence distributed on the single appliances nodes. On the basis of a distributed knowledge (e.g. the intelligent power counter is able to distribute on the bus the instan-
taneous power consumption data), each node, or intelligent socket, endowed with a shared priority map, can decide whether to unplug, or simply reduce his power consumption (Wacks, 1993; Ricci et al. 2005).

4 Conclusions
Certified data bear witness of the large impact of residential utilities and appliances on electrical energy consumption, which substantiate the effort of engineers and manufacturers in optimizing the electrical devices consumption, namely the electrical actuators and motors. This can be supported and achieved by the applied research according two research lines. Specific components and devices can be optimized, which is obtained by using new materials and construction types; a major accomplishments also result from introducing more flexibility and intelligence in the motor regulation, which is realized through static converters and digital control algorithms. The extension to the residential environment of industrial solutions cannot be done unless specific requirements of the home appliances market are considered, such as high reliability and durability, medium performance, low cost. A second encouraging evolution line is related to the extension of home and building automation technologies: in fact an intelligent supervision of the whole home system can makes it still more flexible the use and exploitation of any single appliance, where a strategic role is played by accurate power reading instrumentation, as a decisive support for a precise and efficient electric load management.

5 References


Fans
Energy Efficiency Improvement in Brushless Fan Drives

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Abstract

Energy efficiency continues to be a key issue affecting the ventilation market. Single-phase induction motors, especially shaded-pole motors, have a poor efficiency. Electronically commutated brushless motors work more effectively over a wide range of operating points. A further important advantage of these motors is the easy speed controllability. In fact, power consumption as well as acoustic noises can be strongly reduced with an adjustable speed motor controlling the air volume depending on the cooling demand. But also the efficiency of brushless motors can be improved. This can be achieved by the enhancements of the commutation circuit because the commutation process affects power consumption and mechanical vibration of the motor.

1 Fan drives

Fan and pump systems account for 38-39% of motor systems energy use (Radgen 2002, Elliot 2002). For example, the calculated fan energy consumption in Germany is about 31.8 TWh (Radgen 2002). The share of fans below 1 kW is 18% (5.7 TWh). Energy efficiency continues to be a key issue affecting the ventilation market, and has resulted in a number of overall trends including (AMA Research 2003):

- The fitting of variable speed drives to fan motors
- Increasing use of high efficiency motors

The power consumption as well as the noise level of the fan can be strongly reduced with an adjustable speed motor controlling the air volume depending on the cooling demand. At 50% speed for example, the noise level is typically reduced by 16 dB(A) and the shaft power of the motor is only 12.5% of the rated power.

The efficiency is an important issue also regarding small fans. Even if the power consumption of a single fan is relatively small, the energy reduction potential is important due to the huge volume in which these fans are produced and installed. In addition, a higher motor efficiency means not only lower power consumption but also lower motor temperature and therefore longer life time of the bearing system.

For fan applications, mainly induction motors and electronically commutated (EC) motors are used. Switched reluctance motors are not preferred because of their poor noise behavior. The commutator and the carbon brushes of traditional, brushed dc motors produce electrical interference, acoustic noise and limit the motor life time expectancy significantly. Therefore, this type of motor cannot be used in a large number of applications but it is suitable for example for passenger car applications. Since fans are often supposed to achieve a long life time, it is very advantageous that in squirrel-cage induction motors, as well as in EC motors, only the bearing system is the wearing part. EC motors have some further important technical advantages: wide speed range, easy
speed controllability and high efficiency. However, AC induction motors will remain a considerable part of the market, where low cost positioning is important.

EC motors have a higher efficiency than induction motors, therefore their operating temperature remains lower than that of induction motors. That is particularly true for the comparison between permanent magnet EC motors and single phase induction motors such as shaded-pole or permanent-split capacitor motors. Especially shaded-pole motors used in large number for example in the refrigeration industry have a very poor efficiency. Beneath the higher bearing life time, the lower operating temperature of a high efficiency motor means that the fan does not heat the cooling air flow. In addition, the EC motor achieves its high efficiency in a wide range of working points. In contrast, the efficiency characteristic curve of an induction motor is quite sharp. Therefore, the induction fan motor often works with an actual efficiency that is considerably lower than its catalogue data. As mentioned, the energy consumption of a fan can be considerably reduced by speed control. Thus, speed adjustable EC motors are especially energy saving.

Cost savings and energy savings should be considered as one entity. Unfortunately, more often than not, the purchase price ranks first in most motor buyers' opinion; the importance of long term energy saving is underestimated. However, saving on motor price alone may prove unwise.

![Figure 1: Compact mixed-flow fan with integrated external rotor motor](image)

2 External rotor fan motors

In external rotor motors, the cowl-shaped rotor revolves around the stationary stator. The rotor shaft is integrated into the rotor construction. These motors appear most commonly as spindle motors for hard disc drives and as drive motors for ventilation fans. In these applications, the motor becomes an integrated part of a larger structure.
Fig. 1, for example, shows a compact mixed-flow fan developed for electronics cooling with integrated external rotor motor.

The motor assembly comprises two major sub-assemblies, rotor and stator. At smaller brushless fans, the multi-pole rotor is formed from a ring of plastic bonded permanent magnet material installed within a steel cup. The pole number is typically four or six. In the case of fan motors for higher torque, sintered ferrite magnets are also used. The cup combines the function of magnetic return path, magnet containment and mechanical interface to the impeller. For axial fans, the blades can be directly mounted on the rotor. For centrifugal fans, the external rotor motor can be fitted inside the fan impeller itself. Both, axial and centrifugal versions result in a space-saving fan-motor-unit.

The relatively high inertia of the external rotor is advantageous in minimizing small speed disturbances and reducing acoustic noise. On the other hand, reduced dynamic is not a disadvantage for fan applications. A further benefit of the external rotor construction is the firm connection between all rotating parts in a fan ensuring accurate balancing. As a result, the bearings undergo lower stresses and achieve longer life time.

Figure 2: Backward curved centrifugal fan with integrated EC motor

Fig. 2 shows a backward curved centrifugal fan with an electronically commutated external rotor motor. The stator consists of a stack of externally slotted electrical iron laminations, electrically insulated and wound with enameled copper wire. Since the stator teeth point outward, this motor is relatively easy to wind. Especially the flyer winding technology is very fast and economic. The single tooth winding commonly used in such motors produces very short winding heads, thus allowing space-saving motor design and reduced copper losses. In addition, the motor can be built very compact because of the bearing system integrated into the stator’s interior. The wound assembly is mounted onto the base plate which also supports a printed board containing the drive electronics and the rotor position sensing elements. This results in a very compact design with all the heat-producing components integrated into a single sub-assembly.

By virtue of being installed within the impeller, the motor benefits from efficient cooling, maximizing the life of the product whilst minimizing the overall height of the fan. Simple
motor construction and minimal parts count ensure a highly reliable, cost effective solution. In addition, motor drive electronics can be totally enclosed, allowing the fan to withstand adverse environmental conditions.

3 Electronic commutation

An electronically commutated brushless motor is a permanent-magnet synchronous motor with trapezoidal air-gap flux density fed by commutating electronics. The motor runs in self-synchronous mode; the inverter output frequency (commutation frequency) depends on the rotor speed. Since fans generally do not need high starting torque, low-cost single-phase bipolar (Fig. 3.a) and split single-phase unipolar (Fig. 3.b) motors can be used, too. The commutation circuit of latter motors contains only two power transistors. Because of the relatively poor efficiency and their limited capability for speed adjustment these unipolar motors are normally not preferred for new developments.

Figure 3: Schematic diagrams of typical EC motors
a: single-phase bipolar  b: split single-phase unipolar  c: three-phase

Advantages of the single-phase (unipolar or bipolar) motors are the reduced electronic parts count and the simple winding and insulating system. Disadvantages of such motors are the higher torque ripple and the fact that the motor cannot create an active torque from all rotor positions. That is because the single-phase winding can create only a pulsating but not a rotating magnetic field. Therefore, the start is critical. To guarantee a safe start, the stator has usually a specific design with variable air-gap. This variable air-gap generates an auxiliary reluctance torque which is effective even if
the winding is currentless. Therefore, this reluctance torque can ensure that the rotor is always outside the critical neutral zone in the standstill position. This increased cogging torque, however, can cause a higher solid-borne noise level.

Three-phase bipolar EC motors produce less motor noise, so they are preferred for noise sensitive application, such as HVAC fans in office spaces, clean rooms, etc. In addition, three-phase EC motors have better motor utilization and higher efficiency. Therefore, there are commonly used for higher motor power.

In a three-phase bipolar EC motor (Fig. 3.c), only two phases are current-fed at the same time. Three Hall-effect sensors detect the magnetic field of the rotor. At each rotor rotation of 60° electrical, the output level of one sensor changes, alternately. Then, the next step of the commutation sequence is applied, and the current commutates from one phase winding to the next one. It is also possible to control the commutation without rotor position sensors. For fan motors, the simple and robust back emf method is mostly utilized. The back emf can be easily detected in the currentless, un-excited phase winding. This method does not work at low speed. Fortunately, fans are normally operated only in medium and upper speed ranges. The start is not critical because fans do not need high starting torque.

4 Optimized motor control

At the optimization of EC motors, mechanical construction, magnetic design, winding and insulation system, power electronics and control method can be changed. Not only the motor efficiency, but also motor size, production cost, noise behavior, operating temperature range, supply voltage range, life time expectancy or environmental protection can be improved. Different optimization objectives, however, can lead to different solutions. The motor design for the lowest noise level, for example, does not lead automatically to the lowest production cost or to the best efficiency. The optimization process is therefore always a search for the best compromise. Only the software-realized control method is flexible enough to achieve different objectives for different operating points with the same motor. The state-of-the-art commutation circuits for fan motors are usually controlled by a microcontroller. Since the capability even of low-cost microcontrollers increases continuously, new concepts for improved fan motors will be able to be utilized also for mass production in the foreseeable future.

The conflict between high efficiency and low acoustic noise, for example, can be solved for many fan applications with a control method depending on the motor speed. For fan drives, the motor shaft power is proportional to the third power of speed (Fig. 4). At lower speed, the energy consumption is so low that the motor efficiency is not crucial.
Therefore, the motor noise can be optimized by the control circuit. At higher speed, where the noise of the impeller is normally much higher than that of the motor itself, the motor efficiency has to be optimized. Accordingly, an adaptive control strategy can change the commutation and modulation method depending on the motor speed.

The question is, however, how these commutation and modulation methods can be implemented in a low-cost control electronic circuit without expensive rotor position sensors or complex sensorless rotor estimation methods. One possible solution uses the fact that fans do normally work for long time in a constant working point. Therefore, the fan motor can be started as a traditional sensorless brushless DC motor without any special behavior optimization. After achieving the working point, the control unit changes the control methods and feeds the motor with constant frequency and optimized voltage shape. In doing so, the EC motor works as a high efficiency (or low-noise) permanent-magnet synchronous motor. The control of the modulator is relatively simple because the shape of the winding voltage is not affected by the rotor position. Therefore, the control unit can easily create any sophisticated voltage shape for the optimized motor operation. However, the control unit has to keep under surveillance the synchronous operation of the motor to avoid that the motor falls from synchronism. It can easily doing so for example by monitoring the point of polarity change in the winding current (Lelkes-Krotsch 2005). If the control unit recognizes such a risk it will change the control method and will feed the motor as a traditional EC motor again.

**Figure 4:** Motor shaft power and impeller noise vs. fan rotation speed
5 Commutation of single-phase EC motors

The usual commutation method for single-phase EC motors is inartificial. These fan drives do normally not contain closed-loop current controller. Instead, they work with a square-wave winding voltage. The amplitude of this voltage can be modified by pulse-width-modulation (PWM) for speed adjusting. The control of the transistors in the H-bridge (Fig. 3.a) is very simple. At the same time, transistors T1 and T4, or T2 and T3 are active, in turn. After the control signal of the transistors has been changed, the winding current will change its polarity. Because of the relatively high inductance of the motor winding, however, it cannot occur immediately. For compensating this delay, the commutation process has to be started before the zero crossing of the back emf. Most commonly, the point of commutation is determined by a Hall-sensor detecting the magnetic field of the permanent magnet rotor. Since fan motors work normally only in one direction, the compensated commutation point can be determined by a Hall-sensor positioned before the neutral zone (Fig. 5).

![Figure 5: Stator and PCB for the commutating circuit of a single-phase EC fan motor](image)

This method produces a speed variable pre-commutation time. This pre-commutation time corresponds, however, to a constant electrical angle defined by the number of pole and by the mechanical angle between the position of the Hall-sensor and the neutral point (middle of the slot). Latter angle is fixed by the PCB layout. Therefore, the electrical pre-commutation angle is constant for the motor. This angle can be optimized for a typical operating point, but only for one working condition. For other operating points (different motor speed, torque and/or supply voltage), this pre-commutation angle is not optimal; the motor works with reduced efficiency.

An improved solution is to place the Hall-sensor in the middle of the slot. The microcontroller has to shift the commutation point digitally. In doing so, the pre-commutation angle can be varied easily. As the oscillograms show (Fig. 6), the pre-commutation
angle affects the amplitude as well as the shape of the winding current significantly. Therefore, this control parameter can be used for optimizing the motor features. With the maximization of motor efficiency power consumption and motor temperature can be reduced and life time expectancy can be increased. The technical and economic difficulty in doing so is caused by the continuous measurement of efficiency by the control unit. For this reason, it is recommendable to use a simplified method to adjust the pre-commutation angle at low-cost fan motors.

If the back emf and the winding current have opposite polarity at certain time points the motor works as a brake. Braking periodically means high torque ripple, acoustic noises and poor efficiency. The investigation has showed that the motor efficiency achieves nearly its absolute optimum if the winding current and the rotor position are synchronized (Fig. 7). In this solution, the control unit has to monitor the polarity of the winding current at the time when the rotor achieves its neutral position. This time point is known because at this point occurs an output level change of the Hall-sensor positioned in the middle of the stator slot. If the zero-crossing of the winding current occurs before the edge of the Hall signal, then the pre-commutation angle is too large, that means that the commutation was started too early, and the control unit has to reduced this angle. On the other hand, if the pre-commutation angle is too small, that means that the commutation was started too late, the zero crossing in the current occurs after the edge of the Hall signal. As soon as the control unit recognizes that, it has to increase the said pre-commutation angle. Advantage of this control method is that the control unit only needs the current polarity as additional information (Lelkes-Berbatov 2005). With this steady adjusting of the pre-commutation angle, the single-phase EC motor will work with nearly optimum efficiency in every operating point.
Another solution for efficiency improvement of such fan motors is the modification of the commutation process. At this method, the commutation process is carried out in two steps. Firstly, at a certain pre-commutation angle, the two active power transistors of the H-bridge will be turned off. After that, the winding current flows through the freewheeling diodes. The inductive energy of the winding will be converted into capacitive energy in the link capacitor, and the winding will be currentless. Even if the pre-commutation angle is too large, no negative current can flow because no power transistors are turned on. The active transistors of the next period will be turned on only in the second commutation step. It occurs at the change of pole recognized by the edge of the Hall signal. The investigation has showed that this commutation method is much more robust against changes in the operating point. With this simple modification of the commutation process, the motor efficiency can be improved in a wide range of load condition without the need of any adaptive control mechanism (Lelkes-Göhring 2005).

These examples for sophisticated control strategies show that the efficiency of brushless fan motors can be increased by the control unit. The continuous improvement in the microelectronics will make possible the realization of such methods for the mass market in the foreseeable future.
6 References


A New Type of Fandesign

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Abstract

The Spiral Fan is an invention by Bengt-Olof Drugge in Sweden. The fantype is radially with backward bended wings formed as a part of a spiral. Characteristic for the fan is high efficiency and low noise. The fan is tested by The Swedish National Test- and Research Institute (SP). The capacity of the fan is 2 m³/s and 2 kPa at the Working Point (WP).

A fan of this type has been running in a mining in Kiruna in the north of Sweden since 1996. No disturbance has been observed.

The fan is calculated and designed with the help of a computer program developed by the inventor. In a few minutes the fan is calculated. The manufacturing of the fan is as simple as a common standard fan. The wings are bended according to data from the design program, and since the wings are just bended, and have the same thickness over all, the handle will be quite simple. In a molding process the procedure will be the same as for a standard fan.

1 Background

The inventor started his design work of the fan in 1992. His intention was to get a higher efficiency then the best fans on the market. Bengt-Olof was known as a technician genius, but lack of education in fan design. The mining company LKAB still ordered a fan for installation in the Visiting Mining in Kiruna. The result was very good. The capacity is 11 m³/s and 1.2 kPa. LKAB measured the efficiency to 95 % and the sound to 75 dB(A). But for several reasons no more fan has been installed.

Silenco Eng. was engaged in 2001, and contacted Värme forsk, a service company for the paper&pulp industry in Sweden. Värme forsk coordinate the research for reducing the energy consumption in industries with high electricity use. This year their Scientific Board approved the report from the test at SP.

2 Theory

The theory is based on the following assumptions:

• The area for the fluid has to be constant throughout the inlet, wheel channels and outlet
• The speed through the fan, the radially speed, cannot exceed the speed of the rotation at the inlet
• The difference between the square of the outlet rotational speed and the square of the inlet speed must be higher than the square of the radially speed.

Constant area means that no losses are induced by mass unbalance, which means that energy balance will occure.
This requirement set some limitations of dimensioning. The height of the fan must be \( \frac{1}{4} \) of the inlet diameter. The outlet height must be calculated to the relation inlet/outlet diameter to inlet height. As the area through the channel is constant, mass balanced is received and also energy balance. It means no losses.

Another limitation is the attach angle of the inlet wings. In accordance to the second requirement this angle can't exceed 45 degrees. The spiral must be bended so the wings not force the fluid through the channel. Therefore the wings have lower angle the closer the wings come to the periferi. Designing the wings to fulfill that criterion creates a wingshape according to Archimedes spiral. Another way of explanation:

Suppose a disk rotating at constant speed. Draw a line straight from the center to the periferi with constant speed, just the way we want the fluid to go. The result will also be an Archimedes spiral. That spiral can simply be calculated with a pocket-calculator or a computer.

The third requirement is necessary if the high efficiency and low noise shall occur. If the transportation of the fluid through the channel is created just by the centrifugal forces the transportation is free from losses. At the working point the kinematic vector and the relative pressure vector is redirected from each other and therefore zero-resulting.

3 Dimensioning

Analyze of the fanwheel tested at SP.

Outlet diameter 900 mm
Inlet diameter 450 mm
Inlet height 112.5 mm
Outlet height 56.25 mm
Speed 1500 rpm
Maximum pressure 4496 Pa
Maximum flow 14400 m³/h
Slip (Stodola) 989 Pa
Number of wings 6
Working Point (WP) 7200 m³/h 1753 Pa (3507 W)
Sound 80.17 dB(A) W/m²
Attach angle 35 degrees
The flow can be chosen in a span of 1:10. It means that this fan can be designed for a flow at max 2.8 m³/s down to 0.28 m³/s by just vary the attach angle (a new fan must be built) but at the same pressure and dimensions. The efficiency will stay at a same high level.

The design method allows meeting the most exceptional requirement, i.e. high pressure and low flow and vicing versa.

The tested fan is available for test, measurement and investigation.

The figures above are from a small fan prototype. Capacity is 360 m³/h and free blowing. Working Point is 100 l/sec and 90 Pa.

Dimension: Outlet/inlet/heght: 160/120/30 mm. Noise: 42 dB(A)

Diagram 1 shows the pressure and flow. The dot/line is the calculated maximum pressure. The dotted line is pressure with regards to the slip. The boxes are values measured by SP. The bottom line is the calculated dynamic pressure.
4 SP-test

The test was performed according to ISO 5801. SP is certified to do the test according to that standard.

4.1 Efficiency

SP measured the efficiency to 90%. Higher efficiency was expected and some explanations can be that the fan was more than ten years old, not used and stored outside for the last two-three years. It is also uncertain to know the efficiency of the motor. A 4 kW ABB-motor, type M2AA 112 M and meeting EFF2 energy classification, was used and taken from the shelf. The motor was not individually weighted and was con-
nected direct to the grid at SP, without any control of harmonics and unbalanced voltage. The result was however good enough for Värmeforsk to order a test of the sound.

Diagram 2: From the protocol from SP.

Table 1: Tested values, not converted

<table>
<thead>
<tr>
<th>$P_{\text{input}}$ (W)</th>
<th>$n_{\text{TE}}$ (rpm)</th>
<th>$q_{\text{v1TE}}$ (m$^3$/s)</th>
<th>$P_{\text{FTE}}$ (Pa)</th>
<th>$P_{\text{aTE}}$ (W)</th>
<th>$P_{u\text{TE}}$ (W)</th>
<th>$\eta_{\text{aTE}}$ (%)</th>
<th>$\eta_{\text{eTE}}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4061</td>
<td>1432</td>
<td>1892</td>
<td>1620</td>
<td>3389</td>
<td>3048</td>
<td>90.0</td>
<td>75.2</td>
</tr>
</tbody>
</table>

Input power is 4061 W from the grid. Rotational speed is 1432 rpm. The flow is 1892 m$^3$/s and the pressure 1620 Pa. The power from the motor shaft is 3389 W and the power from the fan is 3048 W. The efficiency is 90.0 % and total efficiency, including motor is 75.1 %. The values are not converted.
4.2 Sound Pressure Level SPL

This test was also performed at SP, according to the ISO 9614-2 standard. The result confirmed the high efficiency, even if it is not known how to correlate efficiency to the sound level. But there is a common idea that high efficiency also gives low SPL. A comparison is done to a fan from Fläkt-Woods (FW) with slightly lower capacity but of same type, radial and back-bended wings.

Table 2: 0-weighted and A- and C-weighted values

<table>
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<th>Octaves</th>
<th>63 Hz</th>
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<th>250 Hz</th>
<th>500 Hz</th>
<th>1000 Hz</th>
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</thead>
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<tr>
<td>FW O-weighted dB</td>
<td>110.8</td>
<td>97.7</td>
<td>93.2</td>
<td>88.8</td>
<td>85.6</td>
<td>78.4</td>
<td>72.6</td>
<td>59.7</td>
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<td>76</td>
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<td>58</td>
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<td>17.7</td>
<td>13.2</td>
<td>8.8</td>
<td>9.6</td>
<td>9.4</td>
<td>14.6</td>
<td>6.7</td>
</tr>
<tr>
<td>FW A-weighted dB(A)</td>
<td>84.6</td>
<td>81.6</td>
<td>84.6</td>
<td>85.6</td>
<td>85.6</td>
<td>79.6</td>
<td>71.6</td>
<td>58.6</td>
</tr>
<tr>
<td>SF A-weighted dB(A)</td>
<td>53.8</td>
<td>63.9</td>
<td>71.4</td>
<td>76.8</td>
<td>76</td>
<td>70.2</td>
<td>57</td>
<td>51.9</td>
</tr>
<tr>
<td>difference</td>
<td>30.8</td>
<td>17.7</td>
<td>13.2</td>
<td>8.8</td>
<td>9.6</td>
<td>9.4</td>
<td>14.6</td>
<td>6.7</td>
</tr>
<tr>
<td>FW C-weighted dB(C)</td>
<td>110</td>
<td>97.5</td>
<td>93.2</td>
<td>88.8</td>
<td>85.6</td>
<td>67.2</td>
<td>66.8</td>
<td>56.7</td>
</tr>
<tr>
<td>SF C-weighted dB(C)</td>
<td>79.2</td>
<td>79.8</td>
<td>80</td>
<td>80</td>
<td>76</td>
<td>57.8</td>
<td>52.2</td>
<td>50</td>
</tr>
<tr>
<td>difference</td>
<td>30.8</td>
<td>17.7</td>
<td>13.2</td>
<td>8.8</td>
<td>9.6</td>
<td>9.4</td>
<td>14.6</td>
<td>6.7</td>
</tr>
</tbody>
</table>

Note that FW, even when A- or C-weighted not exceed the 0-weighted value of the SF (Spiral Fan).

The characteristic of SF is a sensation. The four lowest octaves, 63 to 500 Hz have the same level! The fan is free from point noise.

It is also interesting to compare the C-weighted values to the A-weighted. For the FW the difference is 24.11 dB, but for SF the difference is only 5.8 dB. It means that SF has just 1/64, or 10% low frequency noise level compared to FW.

The National Institute for Working Life has suggested that a machine is free from unnoyable noise if the difference is 15 dB between C- and A-weighted values. It has however not been accepted, and a guess is that the fanindustry seems it at impossibly to fulfill the requirement. SF can however be considered as free from unnoyable noise based on the criteria suggested!
Photos from the test plant at SP
5 Energy saving potential

Most energy is possibly to save in the lower effect areas, depending on that fact there are the highest amount of units and very little has been done to increase the efficiency. Not only the fanwheel is poor, the motors often have very low efficiency. A Shadow Pole motor is seldom better than 12-15% but only used for very small fans and the efficiency of the fanwheels are often just 20-25%, resulting in a system efficiency of 2–4%.

In the industry however, the efficiency is better. The system efficiency for the best fan combined with an EFF1 motor will be more than 80%, if connected to a grid with no harmonics and with well balanced voltages.

By using VSD the capacity can be adapted to actual needs and a lot of energy can therefore be saved, but shall not be confused with efficiency. The efficiency will be negative affected by the VSD, depending of the VSD itself but also of the impact of motor efficiency. Before using VSD carefully calculations must be done. Will it be necessary to oversize the motor, what is the distance between VSD and the motor, is bigger cable size necessary, the noise and last but not least – the EMC problems.

By using a HEM (motor with EFF1 energy classification) the efficiency will be higher but that not always means energy savings, because the speed of the motor is often higher, depending of lower slip, and therefore the energy bill will arise for the user when such a motor is used together with a fan.

5.1 Energy consumption for different size

Table 3: Energy consumption used by fans in Sweden listed for different size. From the “Market Study for Improving Efficiency for Fans” page 37. (http://www.isi.fhg.de/e/publikation/fans/fans-final-version.pdf)

<table>
<thead>
<tr>
<th>GWh</th>
<th>&lt; 1 kW</th>
<th>1 – 10 kW</th>
<th>10 – 50 kW</th>
<th>50 – 100 kW</th>
<th>100 -500 kW</th>
<th>&gt;500 kW</th>
<th>Total kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Centrifugal</td>
<td>4691</td>
<td>2532</td>
<td>3958</td>
<td>921</td>
<td>149</td>
<td>558</td>
<td>12809</td>
</tr>
<tr>
<td>Axial</td>
<td>126</td>
<td>62</td>
<td>365</td>
<td>568</td>
<td>89</td>
<td>335</td>
<td>1545</td>
</tr>
<tr>
<td>Mixed</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Others</td>
<td>0</td>
<td>2</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>Total GWh</td>
<td>4817</td>
<td>2596</td>
<td>4325</td>
<td>1849</td>
<td>238</td>
<td>893</td>
<td>14357</td>
</tr>
</tbody>
</table>

The situation in Sweden is relevant for whole Europe. The energy consumption for small fans is the biggest and has probably the highest saving potential.
The biggest fans are already quite effective and the saving potential are low, just a few percent but of big interest for the user. For the smallest fans the saving potential can be 30 – 50 % but of small interest for the user.

Compare a fan for 100 kW, annually use 8000 hours and a fan for 100 W. The energy cost is 16000 € respective 16 € (at an energy price og 0.02 € per kWh). An improvement of 10 % for the 100 kW is worth 1600 € and an improvement of 50 % for 100 W is worth 8 €. It means that a user will not spend a lot of time to get small fans with high efficiency because the saving potential can be neglected, unless the price is equal or lower.

5.2 Motor improvement

Most of the fan motors are not choiced with carefulness, depending of lack of knowledge in the fan industry. How many fan designers are familar with motors and the special problem in that area? The most common motor type is the Shadow Pole motor, one of the most in-efficient motor on the market. Typical efficiency is about 12 %. It means when needed 200 Pa and 0.1m³/s (20W) a motor of 167 W is needed, if the efficiency of the fan wheel is 100 %. A typical value is however 40%, which means 417 W input. 4.8 % efficiency!

We can offer 50 % efficiency even for the smallest fans, for PC. Typical power is 10 W per fan, but not more than 2 W is necessary when using our fan and motor. It means a savings of 8 W per fan and PC. How many PCs are built annually? 20 millions! Running 12 hours a day means 6.4 GWh or 1.28 million € in savings annually.

A new method of motordesign and fan in one integrated step is under development. Silenco Engineering is together with The University of Lund involved in that project. The motor will be distributed to the periferi of the fan and designed to work on the highest efficient point. Since the Spiral Fan reach the working point at relative low speed, a criteria to get high efficiency from the motor is fulfilled.

6 LCC

The Life Cycle Cost becomes more and more important. Because the fan is free from chokes and vibrations it is probable the bearings will be longlife. However, there is no existing experience enough to get a value on the LCC.

7 The Market

Whenever a fan is used, a Spiral Fan can be chosen.

However, a Spiral Fan can’t replace a standard fan wheel because of the different dimension. Therefore the fan is more interesting in new applications.
The Spiral Fan can be used as a roof fan because of the low noise and that the fan can easily be integrated to the building. If the fan is mounted horizontally the area to the environment is limited and a very low level of noise is emitted.

As a fan for drying timber and buildings the Spiral Fan can be a good choice. The fan can be integrated into an induction own with very high efficiency.

As a cooling fan for electronics, computers and telecom systems, the fan is suitable, because of the relative low height.

For battery driven fan system, as in a laptop, the high efficiency is attractive. Low noise is always a good quality.

In air-condition system, kitchen hoods, cars, you name it....
Pump Systems III
Coating of Pumps in the Perspective of Energy Efficiency

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Hans Andersen, Senior adviser, Teknologisk Institut, Gregersensvej, Taastrup, Denmark

Abstract

This paper brings forward the conclusions and findings from a project on coating of pumps. The project involves pump suppliers, suppliers of coating material, the Danish Technology Institute as well host companies for the field tests.

Danish industrial companies having so far used coating for maintenance reasons. In recent years companies have also recognized that coating improves the energy efficiency of the pumps. Reduction of the energy consumption is a result of the coating process. Depending on which type of coating material is used the pump will have an varying increase in efficiency.

In the table below lifetime economic is created for a specific pump based on a 15 years period:

<table>
<thead>
<tr>
<th>Lifetime economics</th>
<th>Coated</th>
<th>Uncoated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pump cost</td>
<td>7000</td>
<td>7000</td>
</tr>
<tr>
<td>Maintenance - sealing</td>
<td>4875</td>
<td>4875</td>
</tr>
<tr>
<td>Maintenance - wheel</td>
<td>0</td>
<td>4875</td>
</tr>
<tr>
<td>Electricity</td>
<td>180000</td>
<td>210000</td>
</tr>
<tr>
<td>Coating cost (twice)</td>
<td>10000</td>
<td>0</td>
</tr>
<tr>
<td><strong>Total cost 15 years period</strong></td>
<td><strong>201875</strong></td>
<td><strong>226750</strong></td>
</tr>
</tbody>
</table>

The example shows that there is potential especially in the area of electricity consumption and maintenance cost. The example is based on the paper mill mentioned later in the paper – an industrial application with rather low electricity price – anyway the lifetime economic is still very god.

In Denmark there are no pump coating guidelines. how to chose the right material seen from the perspective to increase efficiency and the life time of the pump. This project seeks to gather information, it is collected by literature studies, comprises a series of laboratory tests with different types of coating and operation situations and by field tests on site which include measuring before and after coating.

Coating of pumps

This paper presents theoretical and practical problems in connection with coating of pumps.

Coating is significantly enhancing the performance of centrifugal pumps with regard to energy consumption. Since centrifugal pumps by far, are the most common type of pumps used this paper only deals with this kind of pumps.

Pump efficiency

The power to drive a pump is always greater than the output power of the fluid being pumped. Power is usually lost due to hydraulic losses, volumetric losses and mechani-
cal losses. Efficiency (coefficient of performance COP) is a comparison (ratio) between the power coming out of the system and that put into the system. When efficiency is high, the system is minimizing the losses.

Efficiency during lifetime

Centrifugal pump components are subject to degradation by erosion, abrasion, galling, corrosion and cavitation wear which leads to:

- a gradual reduction of pump efficiency
- increased pump vibration
- reduction of operational life

It has been shown that larger clean water pumps can lose, on average, approximately 5% of their initial efficiency in the first five years of operation (Ref. 1)

Losses of a centrifugal pump

To get a better understanding of what can be done to increase efficiency of a pump, to keep the efficiency on a comparatively high level during lifetime and to increase the operational time of the pump, specific speed \((N_s)\) and the different losses need to be discussed.

Specific speed

Specific speed \((N_s)\) is a non-dimensional design index that identifies the geometric similarity of pumps. It is used to classify pump impellers by type and proportions. Pumps of the same \(N_s\) but of different size are considered to be geometrically similar, with one pump being a size-factor of the other (Ref. 2).

Given the head, flow and speed at the best efficiency point of the pump, the specific speed can be calculated and used to draw some general conclusions about the approximate shape of a pump’s performance characteristics.

The different geometries reflect the fact that an axial flow machine, whether a pump, turbine, or compressor, is more efficient at high specific speeds (high flow rate, low head) while a radial machine, that uses the centrifugal effect, is more efficient at low specific speeds (low flow rate, high head) (Ref. 3).

As the impeller friction losses increase with a lower specific speed of the pump, coating will be of interest from an energy point of view if the pump operates with a low flow rate and high head.
Hydraulic losses

The input to a pump process is typically electrical energy that is converted into mechanical energy by the motor and ultimately hydraulic energy by the pump. This is not an ideally efficient process and we inevitably loose some energy along the way. Generally the hydraulic losses within the pump and the system pipe work are most important accounting for approximately 30% of the energy consumed. This is typically for a well-designed system, in many cases the system losses will be much higher (Ref. 4). In this paper hydraulic losses only refer to the losses that occur in the inlet and outlet of the pump; which are in the magnitude of 15%.

Impeller friction losses

The impeller friction losses refer to the losses which occur as a result of the rotation of the impeller very close to the pump housing. The pump design has great influence on the impeller friction losses, it can increase up to about 15% proportional with a lower specific speed ($N_s$); see figure 1. Furthermore, the size of the friction losses also depends on the surface roughness, rotational speed and impeller diameter. An increase in any of these factors will result in greater impeller losses.

Volumetric losses

Volumetric losses are mainly caused by the existence of a suction-sided sealing gap which serves as a throttle in order to reduce the secondary flow from the impeller outlet to inlet as well as an additional pressure-sided sealing gap which usually belongs to the axial thrust balancing system of a single-stage centrifugal pump. This internal leakage flow strongly depends on the clearance of sealing gaps. In connection with coating of pumps, these losses are of no interest. But you should of course take the opportunity to renovate the pump, if needed, in connection with coating.

Mechanical losses

Mechanical losses are losses in bearings for example. These losses are almost constant and make up only about 1% of the power supplied to the shaft. In connection to coating of pumps, these losses are of no interest.

Cavitation

Pumps can also suffer from cavitation due to the formation and collapse of vapour cavities in the process fluid, leading to material removal.
Description of the present applied technology for coating of pumps

The present applied technology for coating of pumps, exposed to a high level of corrosion and erosion, is a very strong epoxy based material reinforced with ceramics, a so-called composite material.

It’s a material, which is a three-dimensional combination of at least two chemically materials, with a distinct interface separating the components, created to obtain properties that cannot be achieved by any of the single components.

The technology is not old, only 10 years, and was developed in the US in connection with space technology. Only recently, researchers became aware of the high quality properties concerning better protection, longer operational life and energy savings.

The epoxy coating is a binding material, nowadays frequently used in industry due to its strength and adhesion properties. An ordinary epoxy material has 2 – 4 bindings per molecule, but the epoxy applied to composite material has 12 – 14 bindings per molecule, which significantly improve the strength and adhesion properties further.

The composite material can be reinforced with ceramic composites depending of the task of the pump. If the pump has to resist a high level of wear, for example from sand, the ceramic composites added to the epoxy are bigger and have a higher concentration.

The outstanding adhesion properties of the epoxy material binds the ceramic particles so the coating is only slowly affected, even when pumping a very heavily wearing fluid. Different tests show tensile strength exceeding 300 kg/cm² (Ref. 5).

Depending on the task the pump has to carry out, the composite material mix and the different coating thickness will vary. Some coatings are intended for chemical corrosion, others for hot water, and finally some coatings are especially appropriate for wearing liquids. Table 1 show the coating types needed with regard to the kind of fluid pumped.

The ordinary coatings reinforced with small ceramic composites are smooth, whereas the coatings which can resist a high level of abrasion have a higher degree of roughness. The roughness has an influence on the energy efficiency. However, most of the coating types applied are of the smooth type. In fact the smooth coatings are smoother than the metal surface of a new pump.
Table 1: Coating types needed with regard to the kind of fluid pumped

<table>
<thead>
<tr>
<th>Object</th>
<th>Liquid</th>
<th>Usually used coating type</th>
<th>Particle size</th>
<th>Coating thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clean waste water</td>
<td>Ordinary water</td>
<td>Ordinary smooth coating reinforced with small ceramic particles.</td>
<td>&lt; 0,5 mm</td>
<td>400</td>
</tr>
<tr>
<td>District heating water</td>
<td>Ordinary hot water</td>
<td>Ordinary smooth coating with special thermal properties reinforced with small ceramic particles.</td>
<td>&lt; 0,5 mm</td>
<td>400</td>
</tr>
<tr>
<td>Drinking water</td>
<td>Ordinary water approved for drinking</td>
<td>Special and smooth coating with a low degree of toxicity.</td>
<td>&lt; 0,5 mm</td>
<td>400</td>
</tr>
<tr>
<td>Chemical industry or waste water without particles</td>
<td>Corrosive liquid, pH lower than 7</td>
<td>Ordinary smooth coating with special resistance to chemical liquid with a low pH value.</td>
<td>&lt; 0,5 mm</td>
<td>400</td>
</tr>
<tr>
<td>Swimming pools</td>
<td>Corrosive liquid, pH higher than 7</td>
<td>Ordinary smooth coating with special resistance to chemical liquid with a high pH value.</td>
<td>&lt; 0,5 mm</td>
<td>400</td>
</tr>
<tr>
<td>Chemical industry or waste water with particles</td>
<td>Wearing corrosive liquid, pH lower than 7</td>
<td>Less smooth coating with resistance to chemical liquid with a low pH value and reinforced with big particles of ceramics.</td>
<td>1 – 2 mm</td>
<td>3.000</td>
</tr>
<tr>
<td>Sea water with particles</td>
<td>Wearing corrosive liquid, pH higher than 7</td>
<td>Less smooth coating with resistance to chemical liquid with a high pH value and reinforced with big particles of ceramics.</td>
<td>1 – 2 mm</td>
<td>3.000</td>
</tr>
<tr>
<td>Sand pumping</td>
<td>Strongly wearing liquid</td>
<td>Rough coating reinforced with a high concentration of very big particles of ceramics.</td>
<td>2 – 5 mm</td>
<td>6.000</td>
</tr>
</tbody>
</table>

Spin off effects

A pump of high efficiency is of little value if the efficiency falls rapidly with time.

However the degradation processes active on the surface of the pump components can be significantly reduced through the use of appropriate protective coatings.

References where pumps have increased operational life from 3 months to as much as more than 3 years due to coating (Ref. 5).

Coating will first of all reduce maintenance cost. But it will probably also prevent stop downs of the production of an individual industry; for example in connection with lack of cooling water as a result of a pump breakdown. Just a single not predictable stop down of a production can manifold exceed the value of the energy savings, which can be achieved during the operational life of the pump.

Pump relations

A word of caution here The following relations can be found in most references and books on centrifugal pumps. They are valid for a single pump operating at various speed levels.
Flow rate: \[
\frac{rpm_1}{rpm_2} = \left(\frac{\text{capacity}_1}{\text{capacity}_2}\right)
\]

Head/pressure drop across pump: \[
\frac{rpm_1}{rpm_2} = \left(\frac{\text{head}_1}{\text{head}_2}\right)
\]

Power: \[
\frac{rpm_1}{rpm_2} = \left(\frac{\text{power}_1}{\text{power}_2}\right)
\]

From these relations it is evident that an increase in the pump efficiency will need an adjustment of the rotating speed provided that the full benefit is desired to be transformed into an energy saving.

Testing of coated pumps

Several tests have been made during the last 2-3 years to investigate the coatings impact on overall pump efficiency.

In this section results will be shown and discussed for both pumps which have been in use for several years and pumps which are recently been delivered from the manufacturer and therefore haven’t been weared at all.

Several topics will be discussed such as:

- expected efficiency improvement
- differences in improvement of different coating materials
- expected impact on high pressure and low pressure pumps
- partly coating/repair instead of total coating
- lifecycle cost analysis based on test results.

Used pumps, Paper mill and Waste water plant

Figure 1: High pressure used pump / paper mill
A 55 kW centrifugal pump, with a traditional closed wheel, was tested in a testrig for off-shore pumps before and after coating. The coating was a fully inside coat with Chesterton **Arc 855** of both wheel and casing.

In spite the fact that the pump, which has been running for years, did not seem damaged at a first look, figure 1 shows a huge increase in performance after coating the pump. In fact the coated pump at a flow of 2000 liters pr. minute is capable to deliver a pressure of about 7,7 bars instead of 7,2 bars – a 7 percent improvement in hydraulic delivery. Such an improvement of performance is off course a good thing if there is a need for this improvement or if the pump is equiped with some kind of speed control.

The coating also had a very good impact on the overall efficiency of the pump. The overall efficiency was improved from approximately 48% to 61% at a working point of 2000 liters pr. minute. If the control system can handle the improved pump in an efficient way – by speed control – it is possible to decrease electricity consumption by 25-30%.

The cost currently to coat such a pump is approximately 5000 euros (including material). The better efficiency at a working point of 2000 liters pr. minute and 7,5 bars represents a reduction in power consumption of 11 kW. With 6000 running hours and an electricity price of 4 eurocent pr. kWh the yearly saving of the electricity bill exceeds 2640 euro.

Another pump was also tested. This time the aim was to investigate a pump which was installed in a very rough environment (waste water).

The pump was heavily damaged and it was decided to renovate the pump(also by ARC material) before coating.

Figure 2 shows a special shape of the performance curve. The pump is not constructed to produce pressure, but is constructed to move large water volumes with solid material included.

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**Figure 2:** Low pressure used pump / waste water
Figure 2 shows that coating has a positive impact on pump efficiency in the higher pressure area, but of course the pump is not supposed to be driven at these working points.

In the best working point (450 m³/h) the overall efficiency is improved from 50 % to 52 % (4% efficiency improvement), but keep in mind that the comparison is made between a renovated pump and a renovated coated pump.

New pumps, small & low pressure

The next set of data is produced in a test arrangement placed at the Danish Technical Institute. Since it is a new pump it has been possible to compare in three steps:

- promised performance and efficiency from manufacturer
- measured performance and efficiency before coating
- measured efficiency and efficiency after coating.

The pump used in this test is a very common 4 kW centrifugal pump used for both industrial purpose and heat supply, with a traditional wheel as shown in the picture below in both uncoated and coated form:

Figure 3: Small low pressure new pump
Most manufacturers have shown a lot of scepticism towards the coating technology. One of their primary issues is impact on performance when you decrease the inside volume of the pump by coating both the casing and the wheel – thus the fact that we are talking about very thin coating layers.

This issue will to have bigger influence for small pumps, but their is no significant difference in performance for the three sets of data shown in figure 3.

The performance for the tested new pump is almost the same as the data from the manufacturer, measured data before coating and measured data after coating. In fact the only visible difference is a slight improvement when coated in the higher pressure area.

The pump was coated with the very smooth Arc S2 with no regard of which environment the pump is to be installed. The goal was to detect maximum efficiency improvement.

Figure 3 also shows measured overall efficiency for the pump before and after coating. Data from the manufacturer only shows pump efficiency thus they are not comparable with the measured data.

Figure 3 shows that the coating also have a very good impact on overall efficiency for a small new pump. The improvement in the best working point for the pump (35 m³/h and 1750 mbar) is approximately 10 %. The overall efficiency of the pump goes from measured 50% before coating to measured 55% after coating.

The cost of coating this kind of pump in “after service” is presently approximately 1000 euros. The price will definitely go down if the manufacturer include the technology in their own production facilities. The price for a new uncoated pump is approximately 500 euro – motor included.

The pump will in the best working point (35 m³/h) have a power consumption of 3,4 kW uncoated and 3,1 kW in coated form. With 6000 yearly running hours and a electricity price at 4 eurocent pr. kWh the yearly difference will exceed 72 euros. In this perspective there has to be other reasons for coating the pump – lifetime of the pump for instance. Or of course the price for a coating has to decrease.

Remarks according to tests done so far

The paper shows parts of the activities going on right now for promoting coating technology. It has been shown that coating of a lot of different types of pump application has a significantly positive impact on energy efficiency, and with larger volume in the application or/and yearly running hours of a certain amount the energy saving alone already today can finance the coating.

Small pumps will be an important issue in the future. Project activities at the moment investigate if it is possible to gain the main part of the improvement potential only by coating parts of the pump – one side of the impeller for instance.
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6. Thanks to Kjell Alfredsson [kjell.alfredsson@zeta.telenordia.se] for ideas
Reduction of Life Cycle Costs in Pumping Systems by Unexpected Fault Finding

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Abstract

In the city of Miskolc, North Hungary 6,000 homes, 120 community buildings are supplied with heat and hot water of 100 megawatt rated power from a heating plant. In the boiler house one pump is driven by an induction motor of 600 kilowatt fed by an inverter and the same inverter supplies the spare motor, if needed, with frequencies between 20 and 50 hertz (Hz). Drive control provides required speed and torque. This up-to-date pump-system was put into practice by a well-known manufacturer recently. Some weeks after the assembly roller bearings and mechanical components were damaged. The same phenomenon occurred when the spare motor was running. Computerised measurement station certified that mechanical resonance appeared around 10 kHz current harmonics providing pull-up torque together with the self-frequency of the motor which was also 10 kHz. The switching frequency of the inverter had an increase up to 12 kHz and resonances were eliminated. The lesson is that both the switching and the self-frequency must be taken into consideration to reduce down time costs because within a week they approach up to 6-times the initial cost of the drive.

1 Introduction

There are outstanding papers available on energy efficiency and cost-reduction in pump systems mainly due to international conferences on Energy Efficiency and Motor Driven Systems. It is a new scientific research achievement to monitoring pump status operation [1] by combining a minimal number of sensors to an intelligent unit with the aid of a programmable logic controller (PLC) particularly referring to the centrifugal pump. To detect the most important faults of a pump like dry-run recognition, bearing temperature and vibrations is a must. In addition, unexpected faults in electrical drive system have to be found within short time otherwise life cycle cost will be drastically going up as this paper presents the achievement of a project implemented in 2003/04.

The technical background is that one heating plant provides heat of 100 megawatt rated power and hot water for 6,000 homes, 120 community buildings in the city of Miskolc, North Hungary. In the boiler house one pump is carrying a mixture of hot water with small solid particles and the pump is driven by an induction motor (1) with one pump and spare-motor (2) fed by the same inverter. The inverter supplies power output between 20 and 50 hertz (Hz), while frequency 0 Hz is the standstill frequency. Any of these two motors with power output of 600 kilowatt each can be connected to the inverter by the use of a switch. Drive control ensures both speed and torque according to the needs. This up-to-date drive was put into practice by a well-known manufacturer. At the beginning the drive was running in an excellent way. Some time later, however,
unexpected noise was observed and it developed further like knocking noise and hammer beat. Fault finding verified that roller bearings and connecting mechanical components damaged, therefore motor (2) had to be supplied by the inverter due to switch over. Some time later the same phenomenon came up again at this motor. Tests of vibration and eccentricity did not reflect to any manufacturing or assembly faults.

The hypothesis for an immediate fault-finding was that the reason of roller bearing damage was stochastic, sudden and frequent appearances of parasite torque resulting in counter torque braking. Plugging can be carried out by the inverter and/or the supply network and can appear several times within one revolution.

2 Impact of unexpected fault on down time costs

LCC stands for "Life Cycle Cost" and is the total cost for an equipment over its lifetime from the installation to decommissioning [2]. Life Cycle Cost is the sum of the following costs: (i) manufacturing or initial cost, in other term as purchase price of the drive, (ii) installation and commissioning cost including training, (iii) energy costs involving predicted cost for the drive operation, (iv) operation cost mainly referring to labour cost of normal system operation, (v) maintenance and repair costs with routine and predicted repairs inclusive, (vi) down time cost coming from the loss of production, (vii) environmental cost which is contamination from the drive, (viii) decommissioning/disposal cost including restoration of the local environment and disposal of auxiliary services. In addition, financial factors as specific energy price, expected annual energy price increase due to inflation or other events, discount rate, interest rate and life expectancy of drive should also be taken into consideration.

The dominant costs are initial, energy, and to some extent down time costs. The following brief and rough calculation provides comparison among them as follows:

1. Initial cost for the up-to-date pump-driven system for the inverter-motor-control unit is about 600 kW × 165 Euro/kW = Euro 100,000 for one complete unit and approx, one-fourth i.e. Euro 25,000 for the spare-motor. This amount is calculated at a higher rate to present a sharp difference in comparison to the other two types of costs.

2. In heating application a pump-drive system is running with full flow [3] for 2 to 3 weeks a year (duty time) which is about 6%. In close to 80% of the time it is running with less than half of rated flow. The result is that around 15% of time as an average is dedicated to rated flow operation. If the provision of hot water is also counted, 18% of time can be attributed for working with rated flow and the drive works at rated power. Then the number of hours while the drive is running at rated power is the product of 8760 hours and 0.18 thus the effective number of hours is 1,577 per annum.

Bearing in mind that the specific energy cost is 0.12 Euro/kWh, then 600 kW × 1,577 hours per annum × 0.12 Euro/kWh equals 113,544 Euro per annum for the energy cost which is 113.5% of the initial cost.
3. The down time cost is effective if the pump system is not running in the reported case for the appearance of unexpected fault. Assuming that full flow is needed for one home but if heating is being out of service the loss as an average a day is estimated as Euro 3.00. This charge is the income going from the home to the heating plant, then 6,000 homes represent Euro 18,000 down time costs a day. One municipal building accommodating 50 offices, etc. at a rate of Euro 4.00 per day, then Euro 24,000 is the daily loss. Thus, the total down time loss would be Euro 42,000 per day and Euro 292,000 a week which approaches roughly 3-times the initial cost. If it is not the full flow to be counted, then the coefficient of 0.18 should be taken into account and then the average total loss per week would be Euro 52,560. If fault finding takes 2 weeks with the replacement of drives inclusive then down time losses will be ranging between Euro 105,120 and Euro 584,000. All in one, to minimise down time cost is an important cost-effective step.

3 Theoretical background of measurement and analysis

To make sure of the reality of the hypothesis a series of measurements (Fig.1) have been performed as measurement and recording of

(i) waveforms of 3-phase, 0.4 kilovolt (kV) supply network during the operation of pump motor (1).

(ii) 3-phase voltage waveforms supplied by the inverter during the operation of pump motor (1).

(iii) waveforms of currents supplied by the inverter as $i_R$, $i_S$, and $i_T$ at motor (1).

(iv) vibration coming up from motor (1).

(v) waveforms of 3-phase, 0.4 kV supply network during the short-term operation (i.e. four hours) of the pump motor (2).

(vi) 3-phase voltage supplied by the inverter during the short-term operation (i.e. four hours) of the pump motor (2).

The measurements (i), (ii) and (iv) were performed in seven consecutive days. Measurement (iii) was performed by step-by-step changes of pump motor speed in the range of 20 to 40 hertz (Hz) roughly one-by-one hertz frequency. Measurements (v) and (vi) were limited to short-term tests in four hours.

Due to the fact of sudden changes of variables there could not Fast Fourier Transform (FFT) be used. Computerised fast speed data acquisition instrument working on 2 x 6 channels with sample frequency of 30,000 samples per second and per channel was in the focus. This equipment unit [2] provided the presentation of current harmonics between 20 and 15,000 Hz, then mechanical vibration and resonances if occurring because they involve the full range of motor faults.
Figure 1: Schematic diagram presents measuring instruments connection.

Figure 2: Noise and vibration of electrical machines from origin to result.

In order to obtain reliable information there was a computer-aided measurement station developed for fault findings (Fig.3). It was first used for diagnostics in stator windings of induction motors driving hot water pumps [4].

The following parameters were measured and/or monitored:
   a) terminal voltage of motor, both phase and line-to-line values,
   b) line-to-line currents,
   c) speed,
   d) electric power input and
   e) waveforms for recordings
   f) vibration of motor roller bearings.
During the period concerned the induction motor worked in heavy duty operation with constant torque control. The main parameters of voltage to frequency converter are as (a) input parameters: supply voltage: 3 × 0.4 kV, frequency: 50/60 Hz, (b) output parameters: required power 800 kW as maximum according to the needs of the drive, frequency: 0 to 50 Hz, output voltage: 3 × 660 V.

A new monitoring software was capable to take samples in a few second duration in every minute, to evaluate them all but to save only those data differing from the rated values at least by ±10%. Or, in other words, if such current, voltage, and other signals come after each other, then the measured values will be continuously recorded 5 minutes before the appearance of the signals.

The vibration theory [5], [6] and [8] for diagnostics of motors applied in this project is summarised briefly (Fig. 2) in the following section (although it is not a full list):

The vibration of electromagnetic origin can be calculated as:

Stator winding harmonics

1. Instantaneous value of magnetic induction:

   \[ b_{v_i}(t) = B_{v_i} \cdot \cos(v_i \cdot p \cdot \omega - \phi_{v_i}) \]

   where \( x \) - space coordinate in radians round the circumference of core, \( B_{v_i} \) - is the amplitude depending on the air-gap characteristics, \( p \) - number of pole pairs, \( v_i \) - order of the space harmonics,

2. The order of the space harmonics:

   \[ v_i = p \cdot (6g + 1) \]

   where \( p \) = number of pole pairs and \( g \) = whole number, 0, ±1, ±2,
Stator winding harmonics
1. Instantaneous value of magnetic induction:
   \[ b_{s} (t) = B_{v} \cos(\nu \cdot p \cdot x - \omega_{v} \cdot t - \varphi_{v}) \]
   where \( x \) - space coordinate in radians round the circumference of core, \( B_{v} \) - is the amplitude depending on the air-gap characteristics, \( p \) - number of pole pairs, \( \nu \) - order of the space harmonics,
2. The order of the space harmonics:
   \[ \nu = p \cdot (6g + 1) \]
   where \( p \) = number of pole pairs \( g \) = whole number, \( 0, \pm 1, \pm 2, \ldots \)
3. The angular frequency: \( \omega_{v} = \omega_{\lambda} \)
4. The phase angle: \( \varphi_{v} = \varphi \)

Rotor winding harmonics
1. Instantaneous value of magnetic induction:
   \[ b_{\lambda} = B_{\lambda} \cos(\lambda \cdot x - \omega_{\lambda} \cdot t - \varphi_{\lambda}) \]
2. The order of the space harmonics:
   \( \lambda = g \cdot z_{2} + p \)
   \( z_{2} \) - rotor slot number
3. The angular frequency:
   \[ \omega_{\lambda} = \omega_{s} \left[ 1 + \frac{g \cdot z_{2}}{p} (1 - s) \right] \]
4. The phase angle:
   \( \varphi_{\lambda} = \varphi + \arctan \frac{I_{m}}{I_{1}} \cdot \frac{s_{b}}{s} \)
   where \( s_{b} \) = slip belonging to maximum (breakdown) torque \( s \) = slip

Stator slot harmonics
1. Instantaneous value of induction:
   \[ b_{s} = B_{v} \cos(\nu \cdot x - \omega_{v} \cdot t - \varphi_{v}) \]
2. The order of the space harmonics:
   \( \nu = p \cdot (6g + 1) \)
   \( z_{1} \) = number of stator slots \( m \) = number of phases
3. The angular frequency:
   \( \omega_{v} = \omega_{\lambda} \)

Eccentricity harmonics
static eccentricity harmonics: the rotor shaft goes out of alignment with the stator hole axis, in this case the angular frequency of harmonics:
\( \omega_{e} = 0 \)
dynamic eccentricity harmonics:
\[ \omega_{e} = \frac{\omega_{s} (1 - s)}{p} \]

Stator eccentricity harmonics
1. Instantaneous value of induction:
   \[ b_{e} = B_{e} \cos(\nu \cdot x - \omega_{e} \cdot t - \varphi_{e}) \]
2. The order of the space harmonics:
   \( \nu = p \pm 1 \)
3. The angular frequency: (as above)

Rotor eccentricity harmonics
1. Instantaneous value of induction:
   \[ b_{e} = B_{e} \cos(\nu \cdot x - \omega_{e} \cdot t - \varphi_{e}) \]
2. The order of the space harmonics:
   \( \nu = (p \pm 1) \)
3. The angular frequency:
   \[ \omega_{e} = \omega_{s} + \omega_{e} (g \cdot z_{2} \pm 1) \]
Figure 4: 3 phase 0.4 kV supply voltage harmonics of one line

Figure 5: 3 phase current signals and its harmonics

Figure 6: 3D graph of current harmonics in function of inverter frequency

Figure 7: 3D vibration diagram of motor - vertical axis presents the acceleration

Figure 8: Spectrum of the bearing vibration
The vibration frequencies of electromagnetic origin were compared to vibration frequencies of bearings. In case of equation in frequencies and phase from different origins can cause resonance and unexpected shocking of motor. Therefore characteristic frequencies of roller bearing vibration also are to be calculated as follows:

The unbalance and eccentricity of the inner rings and the rotor produce a discrete vibration component with a frequency equal to the rotational frequency of the rotor:

\[ f_{be} = n \]  

(1)

The irregularities in the ball cage and the rolling elements produce vibration at the frequency of the cage speed:

\[ f_{bc} = \frac{r_i}{r_i + r_0} \cdot n \]  

(2)

\( r_i \) - radius of the inner contact surface, \( r_0 \) - radius of the outer contact surface.

![Figure 9: Time and frequency diagram of inverter voltage](image)

The frequency of the vibration of the rolling elements due to their irregular shape, while running about their own axis:
\[ f_{re} = \frac{r_i \cdot r_0}{r_r \cdot (r_i + r_0)} \cdot n \]  

(3)

where \( r_r \) - radius of the rolling element.

Defective rings rise vibration at the frequency:

\[ f_r = \frac{r_i}{r_i + r_0} \cdot Z_b \cdot n \]  

(4)

where \( Z_b \) - the number of balls.

No doubt, the frequencies are influenced not only by the above listed factors, but also by the surface finish and the fit between bearing and housing. The frequency analysis of bearing vibrations provides useful information on bearing defects, manufacturing inaccuracies and installation errors.

4 Measurement results

There were four types of measurements performed as electrical power quality, inverter power output quality both for the motors (1) and (2) plus vibration measurement.

1. Electrical power quality [7] supplied by North Hungary Electric Power Supply Authority (its acronym coming up from the Hungarian initials is ÉMÁSZ) at 0.4 kV network proved to be better than the issues of the related standards and directives (Fig.4).

Each of the line voltages met the standardised quality requirements during the whole-period of measurement. Minimum measured value of the voltage was 392 V, maximum value was 411 V.

For the total period of measurement it proved to be that: \( U_{\text{line}} = 400 \text{ V} \pm 2.75 \% \)

The total harmonic distortion during the measuring period:

\[ THD_U = \sqrt{\sum_{k=2}^{\infty} \frac{U_k^2}{U_1^2}} \cdot 100 < 1.4 \% \]  

(5)

where : \( U_1 \) means the voltage fundamental, \( U_k \) is the \( k^{\text{th}} \) order of voltage harmonic.

2. Inverter power output quality measurement during the operation of pump motor (1) was performed. The inverter is provided with up-to-date power electronic devices and circuits, auto-vector control (AVC) and between 2.5 and 10 kHz frequency-band voltage-flux modulation (FMC). The frequency and beat at well-defined loads can vary automatically and its result is the reduction of noise level appearing from the operation
and also vibration of motor. The measurements were performed on the renewed pump motor (1).

The 3-phase voltage due to FMC application establishes symmetric 3-phase currents and they produce the revolving magnetic flux while meeting the torque requirements (Fig. 9.). The harmonic content of line-to-line currents (Fig. 5 and Fig. 6.) can be found in the range of less than 130 Hz and in characteristic way around the 10 kHz domain their values depend to some extent on the speed.

Total current harmonic distortion:

\[
THD = \sqrt{\sum_{k=2}^{n} I_k^2} / I_1 \cdot 100 < 3.51\%
\]  

(6)

In the spectrum of individual current-harmonic distortion at all measured speeds there was a harmonic component found at unusually high frequency around 10 kHz which can cause distortion particularly at low speed. It is worth mentioning that the current harmonic ratio was less than 3.56% i.e. 4.55 A (amps) which was the maximal value in the domain of 20 to 21 Hz

The self-frequency of the pump motor is also in the domain around 10 kHz, thus together with the relatively low current-harmonic component they are capable to initiate resonances that can play the primary role in the damage of pump motors, mainly the roller bearings.

3. Vibration measurement of motor (1) verified that the vibration around 10 kHz frequency is significant (Figs.8 and 7). It can be stated that the frequency of vibration is identical to the frequency of one well-defined current harmonic supplied by the inverter around 10 kHz, thus resonance is occurring at a high degree.

The motor vibration is complex, the amplitudes of vibration at lower frequencies are the most remarkable ones. The amplitude of the accelerations of vibration around 10 kHz is significantly high and it is decreasing with the increase of speed or frequency at a smaller rate.

4. Inverter power quality measurements during the short-term operation i.e. in four hours presented entirely similar results of pump motor (2) to those ones described under paragraph 2 above.

5 Conclusion

The lesson is that both the switching and the self-frequency must be taken into consideration to reduce down time costs because within a week they approach up to 6-times the initial cost of the drive.
6 References


What are Pump Associations and Governments in Europe and the USA doing with Regard to Energy and Environment

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Introduction

For six years or more the author has been involved in energy related issues and projects affecting pumps and pump systems. Some of the projects have been National and some European Association based, others have been projects for the European Commission.

At national level within Europe there are many existing projects, however this paper will concentrate on the work already carried out and the possible future work to be carried out by Europump and the European Commission in Europe and the Hydraulic Institute and the Department of Energy in the USA.

There is no doubt that the pump industry has move forward dramatically in the last decade and it is clear that structures are now available that enable the users of pumps / pumping systems to operate them more efficiently.

1 History and Background of the European Approach

The European Commission SAVE programme started in 1994 originally focusing on motors and then subsequently moved onto motor driven systems such as Fans, Variable Speed Drives and Pumps. The main goal of the SAVE studies was to set boundaries that could be used to benchmark product efficiency in the future.

The Motor SAVE study succeeded with 80% of the manufacturers of standard motors in Europe agreeing to establish three efficiency bands or classes for their 3-phase TEFV (totally enclosed fan ventilated), 2 and 4 pole, cage induction motors in the range 1.1 to 90 kW.

The motors are arranged in 3 classes: Efficiency 1, Efficiency 2 and Efficiency 3; Efficiency 1 being the most efficient category, and Efficiency 3 the least efficient. The aim is to persuade users to invest in Efficiency 1 equipment.

The system used is voluntary with the manufacturer identifying the efficiency of his product range by using labels. Figure 1 illustrates the minimum basic labels. The ‘Efficiency’ marks are copyright of Gimelec, 11-17, rue Hamelin, 75783, Paris Cedex 16.

Figure 1: European motor efficiency classification labels
Motor efficiency classification bands are illustrated in Figure 2. It is apparent that the spread of Effy 2 motor efficiencies is very wide, (up to 7.6%) in smaller sizes and becomes much narrower (1.1%) in larger sizes. The convergence in larger sizes is realistic since most motors in larger sizes have similar numerical efficiencies, but small differences are very significant in terms of lifetime energy consumption and cost for larger motors.

The report for the Motor SAVE programme recognised that motor driven systems accounted for large amounts of electricity used in industry. New SAVE programmes began on Variable Speed Drives, Compressors, Fans and Pumps.

PUMP SAVE PROGRAMME

In 1999 the European Commission began work on the “SAVE Pump Study”. Initially the study was to be on all pump types in all sectors. However this changed to rotodynamic pumps only for the main SAVE report and then to 3 specific types of pump when categorisation was debated.

The initial data from the SAVE report surprised many in industry,

The total electricity consumption for motors is estimated to be 797 TWh (SAVE II) in the whole of the EU. This is based on the assumption that motors account for 69% of the total electricity consumption of Industry and 38% of total electricity consumption in the tertiary sector.

Figure 3 shows the split of total motor energy consumption, showing that pumps consume approximately 20% of total motor energy consumption, equivalent to 160 TWh pa.

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1 This is based on 1996 data presented in the SAVE II report.
Figure 3: Split of motor energy consumption, by application.

Of the 20% that pumps are estimated to use of the total motor energy consumption, it is estimated that rotodynamic pumps use 73% and positive displacement pumps 27%.

Figure 4: Example of pump performance curves

Figure 4 shows the basic data seen on a rotodynamic pump performance curve. Rotodynamic pumps have efficiency curves that peak at one duty point, move away from this duty point and energy is subsequently wasted.

A further revelation was the estimated energy that could be saved by focusing on certain issues within a rotodynamic pump system;
• selecting a higher efficiency pumps: 3%
• selecting a better sized pump: 4%
• better installation /maintenance: 3%
• better system design: 10%
• better system control: 20%

Total possible energy saving 40%

It was clear that the best possible energy savings would not come from redesigning the hydraulics of a rotodynamic pump. They would come from better system design and control.

The European Commission understood that greater energy savings could come from better systems and control, however as with the motor SAVE programme it chose to pursue categorisation with the pump industry. Due to the many permutations of different types of pumps it was agreed to look at three pump types only, which would operate on clean clear water (up to 95°C).

The three types selected were;

- End Suction Close Coupled
- End Suction Own Bearing
- Double Entry Split Casing

Members of EUROPUMP fully supported this study which resulted in nearly 4000 duty points being accumulated and plotted on graphs. The conclusion was six graphs showing areas of Lower Efficiency Selections, Efficient Selections and Optimum Efficient Selections. Figure 5 below show an example of one of the graphs.

Information on the Pump SAVE study is held on the European Commission and EUROPUMP web sites for customers to download
http://energyefficiency.jrc.cec.eu.int
www.europump.org.
Also in 1998 EUROPUMP formed two new working groups. The first produced a guide which studied; “Attainable Efficiencies of volute casing pumps”

The second group produced a guide which studied; “Operating rotodynamic pumps away from design conditions”

These two guidelines set the benchmark for discussions with the European Commission. The first examining how much more efficiency could be attained in rotodynamic pumps. The second explaining the importance of operating rotodynamic pumps near a possible to the BEP.
SYSTEM AWARENESS

For many years the pump industry has been aware of Life Cycle Cost principles, which look at the complete system, however the formulas used differed from country to country. In 1998 EUROPUMP and the Hydraulic Institute formed an International Working Group to study this phenomenon. The result being that in 2000 they published the international renowned guide “Pump Life Cycle Costs: A Guide to LCC analysis for Pumping Systems”.

The guide took an in-depth look at pump system design and operation, analysing existing pumping systems and effective procurement using Life Cycle Cost.

For many in the Pump Industry this document was and still is a landmark publication and would form the base of future publications and discussions with government bodies, energy agencies and customers.

The European Commission changed from investigating specific industries to gathering information on motor driven systems. A project began named the “Motor Challenge Project”.

The goal was to have web based information on four areas of motor driven systems for customers to review.

- Compressed Air module
- Variable Speed Drive module
- Fan module
- Pump module

Companies that use Motor Driven Systems can request "Partner" status. Through the Motor Challenge, for this they will receive:

- Aid in defining and carrying out an Action Plan, to reduce energy related operating expenses, while maintaining or improving reliability and quality of service;
- Public recognition for their contribution to achieving the objectives of the European Union's energy policy2.

2 By reducing energy use, companies contribute to:
   - minimizing environmental impact, and in particular reducing CO₂ emissions;
   - improving the competitiveness of European industry;
   - reducing dependence on imported energy sources, thus improving the security of European energy supplies.
Organisations that wish to assist MCP Partners in achieving the goals of the Motor Challenge can become Motor Challenge "Endorsers". Endorsers must define and carry out an "MCP Promotion Plan", which details the actions they will take to further the goals of the MCP. Suppliers of equipment and services related to Motor Driven Systems are the primary candidates for Endorser status.

All the contractual documents have been translated into the national languages of the project participants (Danish, English, French, German, Italian and Portuguese). They are available on the web at http://energyefficiency.jrc.cec.eu.int/Motorchallenge/about.htm

The MCP Guidelines define the basic framework and the rules of the Programme. These Guidelines are linked with the separate Module documents for Compressed Air Systems, Pump Systems, Fan System, Drives (electric motors and speed controllers), as well as a module covering Management Policies applicable to motor systems.

In March 2005 the European Commission started its second phase of the Motor Challenge Programme (DEXA) which again will be pursuing energy audits within industry.

In 2001 EUROPUMP and the Hydraulic Institute again formed an International Working Group bringing together the Pump, Motor and Drives industries to look at Variable Speed Pumping and its effect on the pump system and energy reduction.

The guide was published in 2004

Also in 2004 the commission started a new programme called ProMot. The project is an attempt to bring together a data based system, located on a website, that will compare the efficiency of one motor driven system product against another. For some motor driven system products this is not a problem, for others this becomes commercially sensitive information and many have objected to involvement in such a project. EUROPUMP have now launched the "ECOPUMP" initiative which aims not only to achieve eco-efficiency of pump systems in several market segments but also, and most importantly, to communicate Europump efforts to:

- all customers or end users of the pump industry and, in this way, increase their awareness of energy consumption and environmental protection;
- government institutions and stakeholders at European and Member States level in order to express the preference of our industry for voluntary commitments rather than legislative measures.

For more information on ECOPUMP, please contact the Europump General Secretariat, Tel: 0032 2 706 82 37 – Fax: 32 2 706 82 53 – Email: secretariat@europump.org
2 History and Background of the USA Approach

In the USA the focus on motors had started a little earlier than Europe. In 1992 the Energy Policy and Conservation Act (EPACT) was environmental legislation that had been passed to help cut the amount of energy consumed by various industrial and consumer products. The act outlawed simple things like certain types of fluorescent tubes, however a main provision of the act required manufacturers to stop offering motors with rated load efficiencies that fell below a specified minimum. This could be one of EPACT’s most significant measures, because approximately 70 to 75 percent of the electricity consumed by industry is used to run motors.

Whereas many of EPACT’s provisions took effect soon after the act was passed, motor manufacturers had until October 1997 to implement the measure. The final rule was passed by congress in November 1999 it ensured that EPACT establishes energy efficiency standards and test procedures for commercial and industrial three-phase induction motors between 1 and 200 horsepower.

Prior to the publication of the Life Cycle Cost book the Hydraulic Institute had worked with the Department of Energy on a Programme called PSAT, Pump System Assessment tool. PSAT required hydraulic information from the pump industry and EPACT and NEMA motor data from the motor industry. The result was a programme that allowed the pump industry and customers to assess the energy wastage (or not) of pump and motor unit within a pumping system.

The difference between PSAT and other pump related software is that PSAT software & operating data can be used to determine the system operating efficiency and energy consumption.
This means that PSAT can be used to assess pump systems on existing customer sites.

The introduction of the joint EUROPUMP /Hydraulic Institute LCC book reemphasised the system approach and the Hydraulic Institute and the DOE have since moved into jointly sponsored PSAT Qualified Specialist Workshops. The educational approach pursued by the Hydraulic Institute and the US Department of Energy has led to the latest initiative

**PUMP SYSTEMS MATTER™**

In September 2004, the Hydraulic Institute (HI) Board of Directors approved a national pump systems educational initiative called Pump Systems Matter™ (PSM). This programme places a primary focus on pump systems education and outreach and addresses energy savings and total cost of ownership. Pump Systems Matter™ is the first industry-led market transformation initiative in the United States.

Optimization of pumping systems represents a significant opportunity for U.S. companies and municipalities to save money and energy while reducing maintenance costs and increasing productivity.

The HI began the national educational initiative to support the development and deployment of pump system educational materials and tools, administer related training programs and address outreach and educational efforts to various audiences. The primary goal of the education initiative is to transform the market for pump systems and services to one based on system life cycle costs rather than equipment first costs.

As well as the Pump System Matters initiative the HI are also producing a paper that will be presented this July at the American Council for an Energy Efficient Economy (ACEEE) Industrial Summer Study Conference at West Point, NY to an audience of over 250 energy-efficiency and market transformation experts from state, regional and federal agencies and non-government organizations (NGOs). In this regard, the HI are working to show the importance of selecting the proper pump, installing it correctly and maintaining it to operate at its B.E.P. They have already agreed to make a presentation this September to over 200 users at an energy conference in Hawaii and are planning an industry-sponsored Energy Conference in Dallas in October.

The educational approach is also being pursued by the Northwest Energy Alliance in Oregon USA. The Alliance is a non-profit corporation supported by electric utilities, public benefits administrators, state governments, public interest groups and energy efficiency industry representatives. The organization is funded by the region’s electric utilities.

The mission of the Alliance is to work together with these entities to make affordable, energy-efficient products and services available in the marketplace, otherwise known as “market transformation.” The task will be to educate and train the whole chain of people involved, from manufacturing to using the pumps.
CONCLUSIONS

From studies carried out by industry and governments in Europe and the USA it is clear that a system approach can generate the largest energy savings potential within a pumping system.

The pump industry recognises its responsibilities and is committed to work on actions to address energy reductions within pumping systems.

There is now a wealth of web based and literature information from both the pump industry and governments to ensure the right message on energy reduction is being conveyed.

National and International Pump Associations will continue to work with industry and governments on energy and environment related issues to achieve sustainable results.

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The Benefits of Variable Speed Drive for Air Compressors

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Abstract

The study on compressed air systems in the European Union, published (see Radgen 2001) in 2001, highlights the potential for energy savings by optimizing the overall compressed air system, rather than simply improving the efficiency of the individual components.

The understanding of the application and the best possible match between the compressed air requirements and the compressed air generation are prerequisites for any system optimization. All larger compressor manufacturers are offering services to measure and analyze compressed air requirements. System optimization will often focus on improving the efficiency of the compressors, dryers, filters, condense water drains and sophisticated energy savers as control systems are installed to minimize the energy consumption. The result of the European study was a range of between 5% and 50% of potential energy saving in compressed air systems in different companies.

A variable speed driven compressor needs a professional design from the first draft of the compressor. So the electrical systems with the compressor and the compressor are to be co-ordinated with the special interests of speed regulation. Particularly to consider are the points of motor cooling, the vagabonding currents and the vibrations of parts. Special attention must be put also on the electrical supply net, in order to avoid harmonic distortions.

1 Compressed Air System

1.1 Flow

All air consumers of a plant differ and have a flow and a pressure requirement. The required flow is depended on the production load and on the time settings of the different valves and steps of a process. The air demand can be analyzed via an AirScan during week 1. The analysis shows the flow in l/s throughout a day and a week. It also shows the fluctuation of the air demand during the different time schedules.

Figure 1: Air demand during a week
1.2 Pressure

The pressure is important for the efficiency of the compressed air users. If the pressure is too low, the process will take much longer or will not fulfill its task. At the same time, the pressure has a high impact on the energy consumption of the compressors. To produce compressed air at a level required by the consumer would be the most efficient scenario. This means no losses from an over-pressured system and no pressure is lost in the distribution to users.

1.3 Energy

The energy required to compress air is a function of flow and working pressure. Industrial compressors never work fully isentropic, nor isothermic and follow a so-called polytropic compression cycle.

With \( \pi = \frac{P_2}{P_1} \) being the pressure ratio of the final absolute pressure \( P_2 \) over the absolute inlet pressure \( P_1 \), \( c \) being a constant including the machine-specific characteristics, which are not pressure-dependant but flow, and \( \nu \) being the polytropic constant (\( \approx 1.402 \) for air), the energy required is obtained from the following formula:

\[
W = (c) \left[ \pi^{(\nu-1)/\nu} - 1 \right]
\]

For \( P_1 \) to equal an atmospheric pressure of 1 bar (a), the energy \( W \) required to compress a given volume of air is a function of the effective delivery pressure.

Decreasing the final pressure from 7 to 6 bar (e) will decrease the required energy by 10 %, raising the final pressure from 8 to 7 bar (e) would decrease the required energy by 8 %. The lower the final working pressure, the greater the energy saving effect from reducing the working pressure.

1.4 Storage of compressed air

A standard compressor has a load/unload/start-stop regulation in the order of the net compressed air pressure. This typical regulation works in a pressure range of between 0.5 and 1.0 bar. When supplying compressed air to the user whilst the compressor is out of operation or in idle time, the air comes from the depressurization of the vessels and pipes. The volume of this reserve is very limited and the air delivery can bridge seconds or a few minutes at the most. The effect of storage is only possible as a result of pressure deviation from the set point in combination with load/unload/start-stop compressors.
2 Variable Speed Drive for compressors

2.1 Regulation concept

A VSD compressor measures the pressure in the air system and controls the speed of the motor via a frequency converter. A screw compressor is a displacement compressor and every rotation change produces a value in delivery of compressed air.

The important factor for energy savings is that the pressure will be equal to the same value. Related to the load/unload regulation one can save 5-7% of energy from a stable pressure range. Another important factor for saving energy is avoiding the idle time of compressors. The power consumption during idle time is 17-25% of the full load operation. Also, there are some additional energy related processes requiring more energy than expected. The pressure in the internal vessel, especially the oil separator in an oil-injected screw compressor, takes up some further energy. The calculation for an OIS compressor shows, that a 10% idle time operation results in practice in an energy factor of 51% from the load compressor instead of the theoretical 32%. The figures for a 50% idle time operation are 81% in practice and 52% in theory. And for a 90% idle time operation the figures are 96% and 92% respectively. A laboratory of an independent research company measured energy savings of up to 35% for a variable speed driven compressor versus a fixed-speed compressor. (See van Nederkassel, 2004)

Figure 2: The pressure band and the blow off effects

![Diagram](image-url)
2.2 Multi Compressor Regulation

If the air demand is much higher than a VSD compressor flow range, a multiple-compressors solution is required. In this case, a VSD compressor can be operated within a combination of one or more fixed-speed compressors in such a way, that the VSD compressors always operate in the range between the minimum and the maximum speed. The flow of a fixed-speed compressor is limited to 80% of the flow range of a VSD compressor. The fixed-speed compressor can start and deliver the compressed air and never works more in idle time.

Figure 3: Scheme of Regulation with VSD Compressor

An alternative is to use 2 VSD compressors and larger fixed-speed compressors. In this case, the reaction time in the event of a fluctuation in air demand is much quicker. The best possible result can be achieved with an Energy Saver as a controller for the entire compressor station. The Energy Saver controls the speed of the VSD compressors and the start/stop of the fixed-speed compressors. The basic elements for this operation are the compressed air system pressure, the gradient of fluctuation and the specific power requirements from the connected compressors. The Energy Saver is looking always for the best combination of compressors for this specific air demand. The ES can be fitted with an Internet connection option. Every person with a license...
can monitor the compressed air system from anywhere. Data warehouses produce many reports, analyzing the air demand, energy and costs.

Both solutions provide the lowest specific energy consumption compared to using different sizes of compressors with fixed-speed only. A fixed-speed compressor cannot match the exact actual air demand. If the size of compressor is larger than the air demand, the pressure in the air system will increase and all running compressors will have an higher energy consumption. If the size of a fixed-speed compressor is smaller than the demand, the pressure will decrease. But in all cases the pressure has to be higher then the requested level.

The air demand in a plant is always changing, depending on the production load and the time of the different processes using compressed air. A compressor system has to deliver the required compressed air in such a way that the pressure in the air system is stable.

3 Components of the VSD Compressor

3.1 Frequency Converter

Highly efficient PWM (Pulse Width Modulation) frequency converters are using high speed, low loss IGBT’s (Insulated Gate Bipolar Transistors) for low harmonic distortion and minimal electrical losses in the motor.

![Image of Energy Efficiency Insulated Gate Bipolar Transistors]

Figure 4: Energy Efficienced Insulated Gate Bipolar Transistors

Harmonics are related to induced currents and voltages developed by a “non-linear circuit”. Most of the electronic circuits fall in this category.
These currents and voltages superimpose upon the fundamental sine wave to create a deviation in its shape. The extent of deviation is called a “harmonic distortion”.

Un-controlled harmonic distortions cause overheating in motors, transformers and other equipment on the customer’s network.

In order to control harmonics, precise calculations and connection of respective inductance coils, capacitors and reactors are required.

**Electromagnetic Compatibility (EMC directive 8/C9/EEC)**

This is defined as the “compatibility of electronic equipment with the electromagnetic environment, in which they are working”

There are two elements to EMC:

- The equipment should be designed in such a way that it does not interfere with the working of other equipment. This constitutes control.
- The equipment should not be disturbed by electromagnetic emissions from other equipment. This is called immunity.

Uncontrolled speed-regulated equipment emits electromagnetic waves, which will interfere with instrumentation signals and other equipment. If unprotected, it is also susceptible to external electromagnetic waves.
Experience shows that the cost of electronic equipment increases by 30% if control and immunity measures are applied. In order to comply with the EMC Directive, action needs to be taken. RFI filters in VSD units ensure compliance with the Directive.

### 3.2 Motor

A motor for a VSD compressor has a special design in accordance with a fixed-speed motor. The torque must be stable over the full speed range and the fan produces more flow for a better cooling to avoid overheating at the lowest speed. The bearings of the motor must be protected against the vagabond currents. Isolated bearings and brushes are the solution and the running surface of the bearing balls no longer contains any craters.

![Figure 7: Craters in Bearings](image1)

HF straps or armor around the cables are used to discharge induced currents to the motor frames and as an anti-emission measure. Atlas Copco adopts all necessary measures to prevent damage caused by bearing currents.

![Figure 8: Inverter Duty Motor](image2)
All VSD compressors shall be designed for maximum reliability:

- 100 % designed and tested for Electromagnetic Compatibility
  - EU EMC certificate – the most stringent standard
  - Line reactor and RFI filter included
  - All motors are designed for VSD and are protected against bearing currents

- Integrated controls for compressor + converter
  - Converter is protected against overloading by Elektronikon
  - Start/stop and pressure control by the converter and the Elektronikon are fine-tuned during design

- The compressor is mechanically adapted for the full speed range
  - No speed windows for vibrations
  - Changes to oil circuit for the right oil pressure/temperature

3.3 Gearbox and other mechanical components

A screw compressor is a displacement compressor. The compressor stage has some closed areas in which the air will be compressed. Micro-pulsation will arise in the compressed air depending on the speed. The micro-pulsation will cause some parts to vibrate. The first generation of VSD compressors contained speed windows to eliminate the vibrations.

3.4 Coupling

The coupling has to be made from rubber to avoid that the vagabond currents can flow to the bearings.

Figure 9: Vagabond Currents
4 Summary

• Savings of energy
  The use of VSD compressor gives the highest energy saving up to 35 % if the air demand is fluctuated. That is the case in 88 % of all compressor installations.

• Regulation concept
  If there are more as one compressor in combination with the VSD and fix speed compressors are sophisticated regulation is requested.

• Design of the compressor
  A VSD compressor is not a standard compressor with a frequent converter. The design of the compressor has to take in account the specific demands on the total system.

5 References


6 Abbreviations

\( \pi \) pressure ratio \((P_2/P_1)\)

\( P_1 \) absolute inlet pressure

\( P_2 \) absolute outlet pressure

\( c \) constant factor

\( \nu \) polytropic constant

\( W \) energy

\( I \) current

\( V \) voltage

\( \Delta t \) Zeitdifferenz

VSD Variable Speed Drive

OIS oil injected screw compressor

EMC Electromagnetic Compatibility

RFI Radio Frequency Interference
Teamwork is the Key

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Abstract

The use of modern control technology to aid operation and coordination of compressed air systems

This presentation describes the potential of air demand analysis, compressor control and master control coordination of compressed air installations using modern management systems equipped with trend recognition. Furthermore, it addresses the question of how the prospective user/system operator can contribute to making installation of an optimised, highly efficient compressed air system in his business a reality.

1 Neglected savings potential

Primarily used in specialist areas such as diving and mining just over 100 years ago, compressed air, unlike any other medium except electricity, has become a universal source of energy for almost every production line and is essential for today’s industrial applications. Whilst it is common knowledge how electricity is produced, distributed and used most efficiently, many of those responsible for line production are aware simply that the compressed air is there, even though it is equally as important, if not more so, than the electrical supply. No particular thought is given as to how it is actually produced, distributed and used (Fig. 1). The results of these shortcomings were demonstrated by a study at Coburg University, Germany, carried out in conjunction with the European Union sponsored ‘Efficient Compressed Air’ initiative. It showed that less
than ten percent of all compressed air systems offer little or no energy savings potential. The list of areas where energy is wasted is much longer however and the percentages are much higher (Fig. 2):

Figure 2: From: Seitz, Anja: Ergebnisanalyse der von Kaeser Kompressoren durchgeführten Air-Audits für die Kampagne “Druckluft effizient”; Diplomarbeit, FH Coburg, 2004
If you take a closer look at the detailed findings of the study, you can quickly understand why the ‘Save II’ study\(^1\), which took place back in 2000, identified that energy consumption in compressed air systems could be reduced on average by nearly 33% (Fig. 3).

![Possible Energy Savings
33% Energy Savings](image)

Figure 3: Kaeser Kompressoren works photograph

A third of the 80 billion kilowatt hours required annually to produce compressed air in Europe alone amounts to €2.5 billion when calculated at average European energy prices. This therefore raises the question:

2 What’s going wrong?

The big mistake when discussing compressed air systems is to view them as a collection of unconnected individual components and in particular to focus on “the compressor”. If the promises in some system providers’ advertising are to be believed, then all that’s required to reduce energy costs by 35%, or even 45%, is to simply replace the old compressor with a new frequency controlled model. However, installation of a new frequency master control system alone increases compressed air costs by a handsome 60% and consequently proves any such promises to be nothing more than hot (compressed!) air (Fig. 4).

The consequences can be seen throughout the world in countless companies every day: virtually no one knows the exact cost of compressed air production and usage. Furthermore, hardly anyone has the precise air consumption values to hand and the actual amount of energy used to produce the compressed air is often a mystery. Unawareness of compressed air costs often means that a new compressor is simply added wherever it may fit within an existing compressed air ‘system’ in order to meet increased compressed air capacity for a new production line, for example. Such an air installation should not really be referred to as a ‘system’ however, as it will have probably grown haphazardly over time to meet the company’s air demands and comprise machines of various size, manufacturer and age (Fig. 5).

The new unit therefore becomes part of the air network in name only, as a lack of system planning and coordination means that it essentially operates independently. This in turn leads to disproportionately high compressed air costs due to poor load sequencing and, in many cases, compressed air quality.
3 The remedy lies in analysis, not a cure-all

On average, poorly planned compressor systems operate at only up to 50% of their load capacity, leading to excessive idling costs. However, modern compressed air systems are able to achieve load capacities of well over 90% without the addition of an incorrectly touted “cure-all” of a rotary screw compressor equipped with frequency control.

When considering optimisation of a compressed air system, it is advisable to first take a detailed look at the cost structure of such a system (Fig. 6).

![Cost structure of an optimized compressed air system](image)

Figure 6: From: Ruppelt, Erwin: Cost Analysis and Cost Management for Compressed Air systems – Lecture Forum Industrial Trends, Hanover Fair 2003

It quickly becomes apparent that the total operating costs, and in turn energy costs, are the main outlay to be taken into account and not the initial purchase price of the compressors and air treatment equipment, as might be expected. In fact, the operating costs amount to over 70% of system costs when measured over a system lifetime of ten or even 20 years.

The next step is to gather data regarding the company’s compressed air consumption (Fig. 7). The once often used excuse that compressed air system analyses are time consuming, expensive and not really worthwhile is less common today. Relatively simple procedures allow comprehensive compressed air system audits to be completed...
within approximately 10 days and provide data from which energy savings potential and various system solutions can be calculated.

Figure 7: From: Ruppelt, Erwin, Bahr, Michael: Air Supply with IT Efficiency, Hydrocarbon Engineering, May 2005

Which areas are important for the compressed air audit? The best place to start is with the air application itself, as this defines the pressure, volume and quality of the compressed air that is to be delivered by the compressors and air treatment equipment. Business structure and premises layout also influence the air distribution system. Air system analysis must include actual pressure values, pressure drops within the pipe network and/or air treatment systems and also measure leakage. This data is essential
to determine whether additional optimisation measures are necessary in these particular areas. Lastly, the company’s air consumption profile should provide an insight as to which control and master control systems are most suited to each particular case.

4 Success in action

4.1 Hilti, Kaufering Plant, Germany

These facts are reality, not just theory. For example, amongst the many companies who recognised the potential of this systematic, tailored approach to optimisation of its compressed air system and made it a reality, is the German subsidiary of Liechtenstein based company Hilti AG. When it became apparent that the compressed air supply at the Kaufering plant (responsible for production of electrical motors for well known drilling, drill hammer and construction tools) was necessary, Hilti management opted for a comprehensive compressed air audit and invested in a specifically tailored compressed air system. They chose this approach in preference to the allegedly “simple solution” of just installing an additional frequency controlled compressor. One of the key facts that came to light as result of the audit at Hilti’s Kaufering plant was that although the air distribution network was perfectly dimensioned, the use of modern compressors and a state-of-the-art master controller would allow the required maximum pressure to be significantly reduced. As a result, compressed air production was divided between several base- and peak-load compressors. Further cost reductions were made possible through installation of a heat recovery system. Subsequent annual audits ensure that the air system continues to operate at peak performance and can identify areas where leaks may have occurred. After optimisation of the compressed air system was complete, it quickly became clear that the management at Hilti had indeed made a wise decision, as compressed air costs were reduced by 38% as a result.

4.2 ISE, Bergneustadt Plant, Germany

As a leading automotive component supplier, ISE – Innomotive Systems Europe – is in a highly competitive market and, just as other companies in the sector, is constantly looking to minimise costs. Optimisation of the compressed air supply at ISE plays an integral role in the meticulously planned energy saving program introduced more than 20 years ago in the company headquarters at Bergneustadt by Meinolf Koch, Technical Services Director for ISE. The program has achieved impressive results since its launch and continues to be implemented with great enthusiasm and determination.

2 Ruppelt, Erwin: Economical Air Supplies for the Production of Power Tools; Lecture Com-Vac Application Centre (2005)

3 Baetz, Klaus Dieter: ISE – Impressive Savings Everywhere, KAESER-Report 1/2005
This example further illustrates that compressed air system optimisation is an ongoing process and that the bigger view should be taken rather than random snapshots.

![Economical utilisation of compressed air at an automotive OEM supplier's has been achieved by optimising the complete system](image)

Figure 8: Kaeser Kompressoren works photograph

First of all, ISE looked at the air consumer connections and at the air distribution network, which are now leak-free.

The most significant step was the changeover from a decentralized water-cooled compressed air supply to a centralized, ambient air-cooled compressor system (Fig. 8). Furthermore, the new compressors were installed directly next to the heating system in order to ensure the minimal possible distance to the heat recovery system. The air treatment equipment was also comprehensively upgraded and optimised. Regular audits keep air leakage to a minimum and provide complete compressed air cost transparency. The result: an annual cost reduction of €150 000 with increased productivity and consistently decreasing energy consumption for compressed air production.

4.3 Porsche, Plant 1, Stuttgart-Zuffenhausen, Germany

The circumstances at the renowned sports car manufacturer Porsche were very similar to those at ISE. Optimisation of the compressed air supply at Porsche’s Plant 1 eliminated the relatively large pressure differences which had been present at various points-of-use up until then and provided consistent pressure throughout the plant. Areas requiring higher working pressures were supplied by boosters installed locally at the points-of-use.

Following optimisation of the air distribution network, the old water-cooled compressor units were replaced in favour of a modern air-cooled compressor package. Controlled via a master control system, the new installation comprises units of various sizes to allow maximum flexibility with regards to air delivery and load sequencing. The master
control system is also used to monitor efficiency during the regular compressed air audits that take place. It is Porsche’s awareness of the importance of compressed air for production and costing that has made the annual compressed air production savings of nearly 485 000 kWh in Plant 1 possible. The significance of compressed air to Porsche is nicely summarised on a bicycle used by its compressor maintenance staff, as the sign on it reads: “No Air, No Porsche”.

Figure 9: www.druckluft-effizient.de/wettbewerb/sieger2003/photos

In 2003, Porsche was recognised for its efforts in efficient compressed air production and usage and was awarded the ‘Efficient Compressed Air’ industry prize for the most efficient compressed air system by Rezzo Schlauch, the German Secretary for Economic Affairs and Employment (Fig. 9). He stated that compressed air system optimisation is one of the few areas that benefits both business and the environment, as investment in increased compressed air efficiency pays for itself within a very short period due to the significant savings in operating costs.

5 An unbeatable team

Our three examples show that effective optimisation of a business’s compressed air supply cannot be carried out single handedly, but requires close cooperation and teamwork between the user and compressed air system provider in order to be able to reap the rewards of significant savings and increased efficiency. The air user must provide detailed information regarding the compressed air application so that the air system provider (who incidentally should not be viewed as someone who just sells compressors) is able to work closely with the user and be able to design and install a specially tailored compressed air system that meets all of the users needs. A significant step closer to achieving optimal energy efficiency is taken when commissioning a new compressed air supply and cutting-edge technology helps maintain that efficiency. Modern IT-based compressed air management systems are able to perform a wide range of
audit functions and can seamlessly monitor and document all aspects of system performance and efficiency (Fig. 10).

Figure 10: Kaeser Kompressoren works photograph

The study cited at the beginning of this presentation came to the same conclusions as the EU “Save II” study, also mentioned earlier. It found that an average energy saving potential of 30 percent or more is possible, with the systems audited as part of the study showing potential savings of between 18 and 71 percent. However, these values cannot be achieved simply by fixing the symptoms and exchanging individual components of an inefficient compressed air system. Savings can be made only by looking at the bigger picture.

**Below is a list of the key points to consider when optimising a compressed air system:**

1. A compressed air management system with audit capability
2. Peak-load machines with controls set to match demand
3. Mid-load machines with controls set to match demand
4. Base-load machines with controls set to match demand
5. Heat recovery
6. Energy savings potential for compressed air treatment
7. Optimisation of the air distribution network
8. Leakage reduction
9. Optimisation of equipment using compressing air

The sequence of optimisation measures is determined by the actual circumstances within a company. Whatever the case, a detailed system analysis should always be carried out.
Compressed Air System Audit in a Chemical Company

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Abstract

This paper describes the results achieved during a compressed air system audit at a chemical company in Switzerland. The aim of the audit conducted in Muttenz at the site of Clariant Schweiz AG was to analyse the installed compressed air system and its operation in order to identify energy and cost saving potentials. Because there was measurement equipment already installed, it was not necessary to install a new meter. Instead the existing data had to be extracted from the controlled system and regrouped for the analysis. Aggregated data for 2003 and 2004 and a set of detailed data acquired in the course of one week were used for the analysis. The audit identified a number of measures to improve the compressed air system, but had to conclude that the saving potentials at this site are below average. The audit included the compressors, the air treatment and air distribution up to production or storage buildings. The saving potential identified was quantified as about 300 000 kWh/a, or 13.3 % of the compressed air energy demand. The cost savings were calculated to be around 41 852 Swiss Franks.

1 Introduction

The compressed air production at the chemical production site of Clariant Schweiz AG in Muttenz was analysed to identify possible energy and cost saving potentials in the compressed air system. The site covers an area of about 330 000 square meters and has a total output of 75 000 tonnes of special chemicals per year. Besides production and storage facilities, the site also accommodates logistics, process engineering, environmental services and administration.

At the site, compressed air is distributed at two pressure levels. The control air header pressure is 6 bar, the second level for the factory air is 2 bar. Compressed air has to be provided year-round without interruption to secure production. However, the main production takes place from Monday to Saturday morning only.

2 Compressed Air Generation

Two compressed air headers at different pressures meet the requirements at the site in Muttenz. This already saves energy as the air is compressed only to the pressure required. Typically, for each additional bar of compression, energy consumption increases by 6 to 8 %.

2.1 Factory Air

The factory air is produced with a single frequency-controlled low pressure compressor. Table 1 summarizes the technical data of the compressor.
Table 1: Technical data of the factory air compressor

<table>
<thead>
<tr>
<th>Name of compressor</th>
<th>LF1-1</th>
<th>Manufacturer</th>
<th>Aerzener</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>Building 939</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Type of compression</td>
<td>Screw</td>
<td>Model</td>
<td>VM310-2B1</td>
</tr>
<tr>
<td>Type of control</td>
<td>Variable speed drive</td>
<td>Year of construction</td>
<td>1981; installed 1990</td>
</tr>
<tr>
<td>Compressor type</td>
<td>oil free</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nominal power</td>
<td>155 kW</td>
<td>Full load power</td>
<td>163.8 kW</td>
</tr>
<tr>
<td>Idle power</td>
<td>61.7 kW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Free air delivery (max)</td>
<td>55.9 m³/min</td>
<td>Free air delivery (min)</td>
<td>14.4 m³/min</td>
</tr>
<tr>
<td>Heat recovery</td>
<td>Water</td>
<td>Cooling</td>
<td>air / water</td>
</tr>
</tbody>
</table>

If the factory air demand is greater than 55.9 m³/min (3180 Nm³/h), additional air is taken from the control air system and expanded to the factory air pressure. If the factory air requirement falls below 14.4 m³/min (820 Nm³/h), the compressor can switch between idling and minimum air delivery; however, in this case, efficiency decreases sharply, Figure 1. There is a blow-off valve as a second option. In case the factory air demand falls below the minimum level, some of the air can be blown off to the atmosphere to avoid switching the compressor.

![Factory Air Compressor](image)

**Figure 1:** Specific energy consumption of the factory air compressor
2.2 Control Air

For the generation of the control air, 3 oil free screw compressors and 2 oil free piston compressors are installed in two compressor stations serving the control air distribution network. Screw compressors (building 939) and piston compressors (building 934) are situated at different locations but connected via the compressed air system and operated by a master control system. The piston compressor can operate at full and half load with about the same efficiency (50 % FAD; 56 % power consumption). The technical data of the compressors are shown in Table 2.

Table 2: Technical data of the control air compressors

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<tr>
<th>Name of Compressor</th>
<th>LS1-1</th>
<th>LS2-1</th>
<th>LS3-1</th>
<th>LS4-1</th>
<th>LS4-2</th>
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<td>Compression type</td>
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<td>Screw</td>
<td>Piston</td>
<td>Piston</td>
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<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Control</td>
<td>Load; idling; stop</td>
<td>Load; idling; stop</td>
<td>Load; idling; stop</td>
<td>Load; half load; idling; stop</td>
<td>Load; half load; idling; stop</td>
</tr>
<tr>
<td>Compressor type</td>
<td>oil free</td>
<td>oil free</td>
<td>oil free</td>
<td>oil free</td>
<td>oil free</td>
</tr>
<tr>
<td>Cooling</td>
<td>water</td>
<td>water</td>
<td>water</td>
<td>air /water</td>
<td>air /water</td>
</tr>
<tr>
<td>Heat recovery</td>
<td>no</td>
<td>no</td>
<td>water</td>
<td>no</td>
<td>no</td>
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<td>Atlas Copco</td>
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<td>Model</td>
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<td>ZR3-A</td>
<td>ZR 4-A</td>
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<td>Champion 180 TS</td>
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<tr>
<td>Nominal power [kW]</td>
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<td>110</td>
<td>225</td>
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<td>90</td>
</tr>
<tr>
<td>Maximum power [kW]</td>
<td>103</td>
<td>103</td>
<td>186</td>
<td>94.74</td>
<td>94.74</td>
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<tr>
<td>Maximum power half load [kW]</td>
<td></td>
<td></td>
<td></td>
<td>53.05</td>
<td>53.05</td>
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<tr>
<td>Idling power [kW]</td>
<td>22</td>
<td>22</td>
<td>34</td>
<td>12.8</td>
<td>12.8</td>
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<tr>
<td>Max. free air delivery [m³/min]</td>
<td>18.24</td>
<td>18.24</td>
<td>35.16</td>
<td>17.8</td>
<td>17.8</td>
</tr>
<tr>
<td>Max. free air delivery [Nm³/h]</td>
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<td>1037.4</td>
<td>1999.72</td>
<td>1012.38</td>
<td>1012.38</td>
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<tr>
<td>Specific power [kWh/m³]</td>
<td>0.094</td>
<td>0.094</td>
<td>0.088</td>
<td>0.089</td>
<td>0.089</td>
</tr>
</tbody>
</table>

As can be seen from the table, the two ZR3 compressors date from 1974 and one of them is actually out of order. The two ZR3 compressors will be replaced in the near future by two new compressors, one of which will be fitted with a variable speed drive.

2.3 Compressed Air Treatment

Only a very simple air treatment is necessary for the factory air. The air is cooled by two water coolers in line which are followed by a cyclone separator to collect the condensate build-up in the coolers.
The quality of the control air has to meet much more stringent requirements. The required quality is specified based on ISO 8573-1 with a dew point class 3, oil content class 1 and particles class 2. To achieve this quality, filtration and an adsorption dryer are necessary. Each screw compressor has an inline adsorption dryer which is regenerated by the heat of compression, therefore requiring only a small amount of additional energy for drying (0.12 kWh/h electricity). The air from the two piston compressors located in building 934 is treated in a steam regenerated adsorption dryer. The dryer requires electricity and steam for the regeneration process (3.3 kWh/h electricity; 40.3 kWh/h steam @ 12 bar).

2.4 Compressed Air Distribution

An extended compressed air network is installed on site. Only the control air network was analysed in more detail. The pipes are welded and run mostly underground in special channels together with other piping and the power supply. The main dimension of the network is DN150/DN100. Building 939, in which the screw compressors are installed, is located in the middle of the site. The screw compressors are linked to the distribution network with a pipe of DN 150; the piston compressors are linked to the network via a pipe of DN 80. The tank farm, which is about 700 meters away from the compressor station, is the most distant network point. However, the compressed air consumption at this point is very small. The materials used vary depending on when they were installed. Standard steel pipes and galvanized steel pipes have been used. Some parts of the network have already been constructed using stainless steel.

The network has a volume of about 30 m³; in addition two air receivers are installed behind the piston compressors, each with a size of 10 m³.

3 System Audit

The system audit was performed in different steps. The first step was the walk-through audit, followed by the analysis of the macro level data. Finally, the detailed data of a single week were analysed.

3.1 Walk-Through Audit

During the walk-through audit, the different components of the compressed air system were documented by photos. As an example, some of the photos are reproduced here but many more were taken, Figure 2.

The main points documented during the walk-through analysis were the following:

1. Increased temperature in the compressor room building 934
2. High surface temperature of steam regenerated adsorption dryer
3. Old compressors in building 939 partly defective
4. Blow-off line for the factory air compressor
5. Some control air is expanded to the factory air network.
Two air receivers of 10 m³ each in building 934 serving the piston compressors

Two stage piston compressor Compair Champion 180 (LS 4.2) (Control Air)

Two stage piston compressor Compair Champion 180 (LS 4.1) (Control Air)

Steam regenerated adsorption dryer with blower; type Delair; installed behind the piston compressors

Figure 2: Documentation of the compressed air system

3.2 Analysis of Aggregated Data

Due to the fact that the site is organized in different cost centres, each building is equipped with metering equipment for compressed air. The most important meters can be read electronically, but a number are read manually only once a month. Based on the large number of meters, a very detailed picture was able to be compiled and a compressed air balance calculated. Figure 3 shows the compressed air balance for the control air on a monthly basis. The control air demand in 2004 was 18.6 million Nm3/a, a reduction of about 10 % compared to the previous year.
Figure 3: Production and consumption of control air in 2004

The measured consumption is always greater than the measured production by about 5 to 10%. This difference has been significantly reduced compared to 2003, as in 2003 many of the old meters were replaced with new, more accurate ones. Therefore it is assumed that the difference between production and consumption is mainly due to the accuracy of the flow meters used. Figure 4 shows the share of the different control air consumers in the total demand. The numbers shown relate to the number of the flow meter, e.g. flow meter 836 measures the control air consumed in building 939 and flow meter 818 measures the overflow volume to the factory air system. These two flow meters count about 60% of the total control air consumption. This fits well with the positioning of the control air compressors which are also located in building 939.

Figure 4: Share of control air consumers in total consumption
The factory air demand was 5.7 million Nm\(^3\)/a, a reduction of 16.2 % compared to 2003. The share of factory air drawn from the control air network in the total factory air was reduced from 14.4 (2003) to 13.2 % in 2004.

![Factory Air Balance 2004](image_url)

**Figure 5:** Production and consumption of factory air

The factory air is mainly consumed in the building with the flow meter 829. It counts about 80 % of the total factory air demand. The two other important consumers are equipped with flow meters number 830 and 828; however, they do not show a continuous demand throughout the year, Figure 6.

![Consumption of Factory Air by Consumers (2004)](image_url)

**Figure 6:** Share of factory air consumers in total consumption
3.3 Analysis of Detailed Data

From midnight Monday December 6th, until noon on Sunday December 12th, 2004, the data of the control air system was logged at intervals of one minute to analyse the operation of the compressors and the compressed air demand at a higher time resolution. The following diagrams show the compressed air production of each compressor based on the load/half load/no load signal of the compressors. Therefore the volume is given in normal cubic meters. Figure 7 shows the detailed results for each day of the week.

As can be seen, production at the site starts up on Monday morning at 6 a.m. From then until Saturday 6 a.m., the compressor ZR4 runs continuously as the base load compressor without any idling or stops. The fluctuating demand is covered by the two piston compressors. However, on Monday and Tuesday, the ZR3 compressor started up only shortly, which is responsible for increased idling hours. Over the weekend, the compressor air demand is supplied only by the piston compressors. Both piston compressors often switch at the same time. Based on the data acquired during the week, the annual compressed air consumption was calculated. The profile shows that the compressed air demand is very constant over the year; therefore the compressors can achieve a high capacity factor.

The results in terms of energy consumption and costs are summarised in Table 3.

Table 3: Electricity consumption and cost of control air generation

<table>
<thead>
<tr>
<th>Electricity consumption</th>
<th>ZR4</th>
<th>ZR3</th>
<th>ZR3</th>
<th>Champion 1</th>
<th>Champion 2</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>per week</td>
<td>23 178</td>
<td>354</td>
<td>0</td>
<td>8 914</td>
<td>11 014</td>
<td>43 460</td>
</tr>
<tr>
<td>per year (52 weeks)</td>
<td>1 205 243</td>
<td>18 433</td>
<td>0</td>
<td>463 509</td>
<td>572 734</td>
<td>2 259 919</td>
</tr>
<tr>
<td>Share of load kWh</td>
<td>99.18%</td>
<td>64.60%</td>
<td>0</td>
<td>96.72%</td>
<td>98.09%</td>
<td>98.12%</td>
</tr>
<tr>
<td>Cost for load operation (CHF/week)</td>
<td>2 758</td>
<td>27</td>
<td>0</td>
<td>1 035</td>
<td>1 297</td>
<td>5 117</td>
</tr>
<tr>
<td>Cost of idling operation (CHF/week)</td>
<td>23</td>
<td>15</td>
<td>0</td>
<td>35</td>
<td>25</td>
<td>98</td>
</tr>
<tr>
<td>Cost for load operation (CHF/year)</td>
<td>143 440</td>
<td>1 429</td>
<td>0</td>
<td>53 796</td>
<td>67 419</td>
<td>266 084</td>
</tr>
<tr>
<td>Cost of idling operation (CHF/year)</td>
<td>1 190</td>
<td>783</td>
<td>0</td>
<td>1 825</td>
<td>1 309</td>
<td>5 107</td>
</tr>
</tbody>
</table>

Free air delivery [m³]

| per week | 260 718 | 2 433 | 0 | 95 259 | 119 663 | 478 073 |
| per year (52 weeks) | 13 557 358 | 126 527 | 0 | 4 953 464 | 6 222 462 | 24 859 811 |
| Energy cost [CHF per 1000 m³] | 10.67 | 17.48 | 11.23 | 11.05 | 10.91 |
| Specific power [kWh/m³] | 0.089 | 0.146 | - | 0.094 | 0.092 | 0.091 |
The base load compressor ZR4 is responsible for more than 50 % of the electricity consumption and produces more than half the compressed air required. Compressor ZR3 only operates to a very small extent; however, based on the higher number of idling hours, the specific power of this compressor is the highest.
4 Optimizing Potential

A set of optimizing measures were identified based on the results of the analysis. The first measure aims to further reduce the idling time of the compressors. However, it should be noted that the share of full load consumption is already higher than 98 %, therefore only a small saving is possible. By optimizing the control strategy, especially on Monday morning and over the weekend, the idling hours of the compressors could be further reduced. These savings could be achieved without additional investments, only parameter changes at the master control are necessary. It was calculated that the savings would be 15 000 kWh/a or 1 804 CHF/a.

The second measure was the improvement of the factory air generation, either by installing an additional small factory air compressor to avoid the blow-off of factory air, or using the overflow from the control air system. An additional smaller compressor and a replacement of the old factory air compressor would save about 64 129 KWh or 7 695 CHF/a. Compared to the necessary investment of about 60 000 CHF, however, this measure will not be economic if the existing compressor does not have to be replaced anyway.

An improvement potential was also identified at the compressed air treatment. With a dew point of -44 °C the steam regenerated adsorption dryer was operating far below the required dew point of -20 °C. If the dew point is increased, the cycle time is extended and the steam consumption for regeneration is reduced. An energy saving of 117 676 kWh steam and 9 636 kWh electricity could be achieved, equivalent to a saving of 7 040 CHF/a.

Due to the continuous operation of some parts of the production, it was not possible to determine the leakage rate over the weekend. To get a feeling for the costs involved, a rough estimate was made. A leakage rate of 2.5 % was assumed in the main compressed air distribution system and a leakage rate of 30 % in the distribution behind the flow meters together with a repair rate of one third. Under these assumptions, reducing leaks in the main distribution system could save 1 947 CHF/a; leakage reduction in the secondary distribution system could save an additional 23 369 CHF/a.

In total, an electricity saving potential of 299 733 kWh/a could be achieved by the measures identified. The cost saving would be 41 852 CHF/a. Only a small fraction of the savings would be able to be realized economically. Those measures which require capital investments should be considered if replacement of a compressor is planned for other reasons. The results of the analysis can be summarized as follows: the compressed air supply at the Muttenz site of Clariant is highly efficient and only minor additional improvements could be achieved. This is mainly based on the fact that the load share is already 98 %, a value which leaves only little room for improvement.

Acknowledgement: The work presented here was supported by the Swiss Federal Office of Energy (SFOE) under contract No. 150 896 and Clariant Schweiz AG. We would like to thank Clariant for the permission to publish the results of the audit conducted at the production site in Muttenz, Switzerland.
Efficient Use of Electrical Motor Systems in Thermal Waste Plant

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Abstract
In thermal waste treatment plants, a significant volume of electrical energy is required for internal use in addition to the production of heat and electricity. Most of this internal consumption is required for operating electrical machines and appliances.

The objectives of this research project are to make an approximate evaluation of the potential for more efficient use of electricity in the Turgi waste treatment plant, to draw up a catalogue of measures for reducing energy consumption and assess the options for their implementation, and to make a projection concerning energy efficiency potential in all waste treatment plants in Switzerland.

Using Turgi waste treatment plant as a model, an evaluation of the potential for increasing efficiency in the area of electricity consumption was carried out. Energy-relevant processes and process technologies have been analysed directly on site in order to draw up a catalogue of optimisation measures. A series of tests have been made in order to analyse specific processes in greater depth. The described measures have been evaluated and classified, taking account of their feasibility and economic viability.

A basic projection model was used to assess the potential for increasing the degree of electrical energy efficiency in all of Switzerland’s waste treatment plants.

Depending on how effectively the various measures can be implemented, the Turgi waste treatment plant has the potential to save between 1.7 and 2.2 GWh per annum. Measured against its internal consumption of 17 GWh, this would be equivalent to annual savings of between 10 and 13 percent. Savings of 4 percent can be achieved through the measures defined in the catalogue that have already been implemented.

The projection of the potential increase in efficiency in all thermal waste treatment plants in Switzerland indicates annual savings of around 38 GWh, which is equivalent to the electricity consumption of approximately 10,000 private households.

1 Current situation

The Turgi thermal waste treatment plant produces energy from residential waste. It treats an annual volume of around 113,000 tonnes of waste from approximately 200,000 inhabitants. The steam that is produced from the combustion process is converted into electricity with the aid of steam turbines, and in addition the waste treatment plant feeds heat into the Turgi-Siggenthal district heat network. The Turgi plant produces approximately 35 million kilowatt hours of heat and around 85 million kilowatt hours of electricity per annum, and the main waste products are flue gases, waste water and slag.

The various waste materials run through a variety of processes within the plant, which has a high level of own energy consumption (approx. 17 GWh) due to the large volume of waste to be treated.
2 Objectives, targeted results and procedure

The project set out to achieve the following objectives:

- To make an approximate evaluation of the potential for more efficient energy use in waste treatment plants
- To draw up a catalogue of measures for reducing energy consumption and assess the options for their implementation

Targeted results:

- Detailed descriptions of energy-relevant processes
- List of potential measures that give rise to lower energy consumption, taking account of economic viability and feasibility
- General findings relating to efficiency potential in thermal waste treatment plants

The following procedure was chosen for carrying out the project:

- Analysis of processes and process technologies in the Turgi waste treatment plant
- Detailed study of energy consumers for which a significant energy efficiency potential was assumed
- Listing of energy efficiency measures that make it possible to achieve the objectives through the optimisation of technologies and processes
- Evaluation of measures relating to feasibility and economic viability.
3 Description of the various processes

The descriptions below only concern those processes in which specific measures aimed at increasing energy efficiency were formulated. The descriptions are presented in the order in which the processes take place within the Turgi waste treatment plant.

3.1 Preparation and combustion of waste

The Turgi plant has two combustion lines, each of which comprises a furnace, an electric filter and a flue gas cleansing facility. The NOx catalyser and chimney are shared by both combustion lines.

Figure 2: Diagram of combustion facilities at Turgi waste treatment plant

The delivered waste is tipped into special bunkers via closable apertures. Operation of the bunkers is energy-intensive since the waste has to be constantly distributed, separated and conveyed to the furnaces by a hydraulic crane. Any bulky material has to be mechanically broken up with the aid of a shredder before it is passed on for processing. The shredders, which are operated with hydraulic drives, often give rise to peak loads of up to 450 kilowatts.

The oxidation of the waste material in the furnaces is regulated via a control system. Here the volume of air required for combustion is calculated, taking account of the nature of the waste material and other parameters, while maintaining the necessary level of oxygen. For combustion purposes, primary air is taken in via the bunkers and fed beneath the waste grid into the furnace. For post-combustion purposes, secondary air is blown into the furnace via special nozzles. A certain amount of flue gas is fed back into the furnace for further oxidation.

Primary air is extracted from the waste bunker and blown beneath the waste grid by a radial fan that is driven by an electric motor with a frequency converter. The prescribed
volume flows to the various furnace segments are prepared in the control system. The apportioning and distribution of primary air in the furnace segments is secured via three valves beneath the grid on the basis of the prescribed volume flow. To avoid excess pressure in the air duct, the air pressure can be reduced via a fourth valve that is closed during normal operation. The motor for the primary ventilator in combustion line OL4 has a nominal capacity of 75 kilowatts.

The secondary air supply is extracted from the slag level or waste bunker and blown into the post combustion furnace via nozzles. The additional oxygen gives rise to the combustion of flue gases at a temperature of over 850° C. The distribution of the air is secured with the aid of regulating valves. The total volume is regulated via an adjustable speed ventilator. The secondary unit heating system has been designed so that processing can continue at full load even if the flue gas recycling system should cease to function. The motor for the secondary ventilator in combustion line OL4 has a nominal capacity of 90 kilowatts.

A certain amount of flue gas is fed back into the furnace for further oxidation. The distribution of air is secured with the aid of regulating valves. The total volume is regulated via an adjustable speed ventilator. The prescribed volume is prepared in the control system. The motor for the ventilator for feedback of flue gas in combustion line OL4 has a nominal capacity of 110 kilowatts.

3.2 Treatment of flue gas

Flue gas is fed by means of induced draught ventilators from the furnace through the electrostatic filters, the flue gas cleansing unit and the NOx catalyser, and is then released into the atmosphere via a chimney. The motors for the induced draught ventilators have a nominal capacity of 920 kilowatts.

In the flue gas cleansing unit, pollutants and ash are extracted by means of water injection. The water flows in a closed system and is purified in its own treatment plant. The catalyser for reducing NOx emissions operates at a temperature of approx. 240° C. The flue gas is heated to the required operating temperature with the aid of an oil burner. This process requires approximately 1 million litres of heating oil per annum.

3.3 Energy production

The hot exhaust arising from the combustion process is used to produce steam. The saturated steam is converted into electricity via two high-pressure turbines. The thermal energy is used for internal heating purposes as required, and for supplying the district heat network.

The turbines are cooled with industrial grade water that is taken from the Limmat river. The motors for the non-regulated cold water pumps have a nominal capacity of 110 kilowatts each.
4 Optimisation potentials

From our evaluation of the various processes we were able to identify the following potential measures for increasing the level of energy efficiency:

Table 2: Potential measures for optimisation of energy efficiency

<table>
<thead>
<tr>
<th>Pos</th>
<th>Prozess</th>
<th>Anlage</th>
<th>Gerät</th>
<th>Massnahme</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>Primary air supply</td>
<td>Combustion line 4</td>
<td>Motor and ventilator</td>
<td>Optimise efficiency</td>
</tr>
<tr>
<td>M2</td>
<td>Primary air supply</td>
<td>Combustion line 4</td>
<td>ACC regulator for controlling</td>
<td>Reduce set point of air pressure</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>regulating valve beneath grid</td>
<td></td>
</tr>
<tr>
<td>M3</td>
<td>Primary air supply</td>
<td>Combustion line 3</td>
<td>ACC regulator for controlling</td>
<td>Reduce set point of air pressure</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>regulating valve beneath grid</td>
<td></td>
</tr>
<tr>
<td>M4</td>
<td>Primary air supply</td>
<td>Bunker</td>
<td>Air intake valve</td>
<td>Automate air supply valve</td>
</tr>
<tr>
<td>M5</td>
<td>Primary air supply</td>
<td>Combustion line 4</td>
<td>Motor, ventilator and regulators</td>
<td>Replace with small decentral</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>variable speed ventilators</td>
</tr>
<tr>
<td>M6</td>
<td>Primary air supply</td>
<td>Combustion line 3</td>
<td>Motor, ventilator and regulators</td>
<td>Replace with small decentral</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>variable speed ventilators</td>
</tr>
<tr>
<td>M7</td>
<td>Primary air supply</td>
<td>Combustion line 3</td>
<td>Rotation regulator</td>
<td>Replace with FU controlled</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>motors</td>
</tr>
<tr>
<td>M8</td>
<td>Secondary air supply</td>
<td>Combustion line 4</td>
<td>Motor and ventilator</td>
<td>Optimise efficiency</td>
</tr>
<tr>
<td>M9</td>
<td>Secondary air supply</td>
<td>Combustion line 4</td>
<td>Motor and ventilator</td>
<td>Bypass ventilator with adjusted</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>nominal output for normal</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>operation</td>
</tr>
<tr>
<td>M10</td>
<td>Secondary air supply</td>
<td>Combustion line 3</td>
<td>Rotation regulator</td>
<td>Replace with FU controlled</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>motors</td>
</tr>
<tr>
<td>M11</td>
<td>Recycled air feedback</td>
<td>Combustion line 4</td>
<td>Motor and ventilator</td>
<td>Optimise efficiency</td>
</tr>
<tr>
<td>M12</td>
<td>Delivery of waste</td>
<td>Bunker</td>
<td>Transport, storage and</td>
<td>Reduce distances / lift work</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>distribution system</td>
<td></td>
</tr>
<tr>
<td>M13</td>
<td>Delivery of waste</td>
<td>Shredder unit</td>
<td>Control</td>
<td>Install switch for standby</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>mode</td>
</tr>
<tr>
<td>M14</td>
<td>Delivery of waste</td>
<td>Shredder unit</td>
<td>Oil cooler</td>
<td>Replace with water cooling</td>
</tr>
<tr>
<td>M15</td>
<td>Flue gas extractor</td>
<td>Combustion line 3</td>
<td>Flue gas rinsing facility</td>
<td>Reduce operating pressure</td>
</tr>
<tr>
<td>M16</td>
<td>Flue gas extractor</td>
<td>Combustion line 4</td>
<td>Flue gas rinsing facility</td>
<td>Reduce operating pressure</td>
</tr>
<tr>
<td>M17</td>
<td>Flue gas treatment</td>
<td>NOx catalyst</td>
<td>Flue gas heater</td>
<td>Reduce pollution by increasing</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>reaction temperature</td>
</tr>
<tr>
<td>M18</td>
<td>Flue gas heating</td>
<td>NOx catalyst</td>
<td>Oil burner</td>
<td>Replace with saturated steam</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>heat exchanger</td>
</tr>
<tr>
<td>M19</td>
<td>Energy production</td>
<td>Steam turbines</td>
<td>Cold water pumps for turbines</td>
<td>In winter, cool with only one</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>cold water pump</td>
</tr>
<tr>
<td>M20</td>
<td>Auxiliary systems</td>
<td>Ventilation systems</td>
<td>Air supply/extraction for</td>
<td>Introduce temperature-based</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>shredder unit</td>
<td>rinsing</td>
</tr>
<tr>
<td>M21</td>
<td>Auxiliary systems</td>
<td>Ventilation systems</td>
<td>Air supply/extraction for</td>
<td>Introduce temperature-based</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>various secondary zones</td>
<td>rinsing</td>
</tr>
<tr>
<td>M22</td>
<td>Auxiliary systems</td>
<td>Ventilation systems</td>
<td>Air supply/extraction for</td>
<td>Introduce rinsing</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>various secondary zones</td>
<td></td>
</tr>
<tr>
<td>M23</td>
<td>Load management</td>
<td>Interruptible</td>
<td>Load controller</td>
<td>Installation of load controller</td>
</tr>
<tr>
<td></td>
<td></td>
<td>electricity</td>
<td></td>
<td>to increase peak load output</td>
</tr>
</tbody>
</table>

4.1 Evaluation of the various measures

All the measures listed in Table 1 have been evaluated from the point of view of their feasibility and economic viability. The following specific measures are described and evaluated below as examples.

The following abbreviations were used in this study:
### Table 3: Technical terms

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Meaning</th>
<th>Unit</th>
<th>Remarks and definitions *)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>Output</td>
<td>[kW, MW, GW]</td>
<td>Electricity</td>
</tr>
<tr>
<td>∆P</td>
<td>Change in output</td>
<td>[kW, MW, GW]</td>
<td>Electricity</td>
</tr>
<tr>
<td>∆E</td>
<td>Change in energy</td>
<td>[kWh, MWh, GWh]</td>
<td>Electricity</td>
</tr>
<tr>
<td>p</td>
<td>Pressure</td>
<td>[mbar]</td>
<td>Pneumatics, relative levels</td>
</tr>
<tr>
<td>∆p</td>
<td>Change in pressure</td>
<td>[mbar, %]</td>
<td>Pneumatics, relative levels</td>
</tr>
<tr>
<td>η</td>
<td>Degree of efficiency</td>
<td>[ ]</td>
<td></td>
</tr>
<tr>
<td>∆η</td>
<td>Change in degree of efficiency</td>
<td>[ ]</td>
<td></td>
</tr>
<tr>
<td>V</td>
<td>Volume flow</td>
<td>[m³/s, m³/h]</td>
<td>Pneumatics, hydraulics</td>
</tr>
<tr>
<td>∆V</td>
<td>Change in volume flow</td>
<td>[m³/s, m³/h]</td>
<td>Pneumatics, hydraulics</td>
</tr>
<tr>
<td>_mess</td>
<td>Measurements</td>
<td>e.g. P_mess = measured electrical output</td>
<td></td>
</tr>
<tr>
<td>_setp</td>
<td>Set points</td>
<td>e.g. p_soll = pressure set point</td>
<td></td>
</tr>
<tr>
<td>_act</td>
<td>Current levels</td>
<td></td>
<td></td>
</tr>
<tr>
<td>_nom</td>
<td>Nominal level</td>
<td>e.g. P_nenn = nominal electrical output</td>
<td></td>
</tr>
</tbody>
</table>

### Table 4: Commercial terms

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Meaning</th>
<th>Unit</th>
<th>Remarks and definitions *)</th>
</tr>
</thead>
<tbody>
<tr>
<td>JK</td>
<td>Annual costs</td>
<td>[CHF]</td>
<td>Annual costs of a measure</td>
</tr>
<tr>
<td>IK</td>
<td>Investment costs</td>
<td>[CHF]</td>
<td>One-time investment costs of a measure</td>
</tr>
<tr>
<td>a</td>
<td>Depreciation period</td>
<td>[years]</td>
<td>Depreciation period for accounting purposes</td>
</tr>
<tr>
<td>z</td>
<td>Interest rate</td>
<td>[%]</td>
<td>Interest rate on capital</td>
</tr>
<tr>
<td>Z</td>
<td>Interest costs</td>
<td>[CHF]</td>
<td>Annual interest costs of an investment</td>
</tr>
<tr>
<td>ROI</td>
<td>Return of investment</td>
<td>[years]</td>
<td>No. of years until an investment is amortised, taking account of gross yield and interest costs</td>
</tr>
<tr>
<td>BE</td>
<td>Gross yield</td>
<td>[CHF]</td>
<td>Annual yield of a measure from energy transaction, less associated resource costs</td>
</tr>
<tr>
<td>NE</td>
<td>Net yield</td>
<td>[CHF]</td>
<td>Gross yield less associated interest costs and depreciation</td>
</tr>
</tbody>
</table>

*) In some cases, project-related definitions
4.1.1 M4 Automate air supply valves in bunkers

<table>
<thead>
<tr>
<th>Measure</th>
<th>Primary air supply</th>
<th>Bunker</th>
<th>Air intake valve</th>
<th>Reduction of pressure drop in bunker</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Primary air for combustion lines is extracted from the bunkers (at night, OL3 only). Separate air supply valves must be closed when unloading gates are open. Since these are not automated they are effectively always closed, and this increases the electricity consumption of the primary ventilators. Measures showed that if the air supply valves are automated, it is possible to reduce the pressure drop by approx. 10 mbar.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>Efficiency potential (electricity)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>∆E = ∆P * V * t ; ∆P = P_mess * ∆p; t = 8760 h</td>
<td>119'574 [kWh / Jahr]</td>
<td>38'979 [kWh / year]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mean energy re-purchase tariff: 6.5 Rappen/kWh</td>
<td>7'772 [CHF / Jahr]</td>
<td>2'534 [CHF / year]</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>Estimated costs</td>
<td>Investment costs (IK)</td>
<td>8'000 [CHF]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Annual costs (JK)</td>
<td>693 [CHF / year]</td>
<td>693 [CHF / year]</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>Viability (ROI) (years)</td>
<td>5.4</td>
<td>3.4</td>
<td>Short-term measures</td>
</tr>
</tbody>
</table>

Conclusion

This measure results in savings in the area of primary air supply.

4.1.2 M6 Replace air distribution system beneath grid in furnace line 3

<table>
<thead>
<tr>
<th>Measure</th>
<th>Primary air supply</th>
<th>Combustion line 3</th>
<th>Ventilation and regulators</th>
<th>Replacement of air distribution system (regulators)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Central primary air ventilator and valve system beneath grid should be replaced by 4 separate air-flow ventilators.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>Existing solution using regulators results in high pressure losses in primary air supply. Eliminating the valves reducing the operating pressure can increase the level of efficiency by approx. 35%. The mean power consumption of the primary ventilator is 35 kW.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>Efficiency potential (electricity)</td>
<td>∆p = 35%; P_mess = 39 kW</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>in [kWh / Jahr]</td>
<td>119'574</td>
<td>38'979</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mean energy re-purchase tariff: 6.5 Rappen/kWh</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>in [CHF / Jahr]</td>
<td>7'772</td>
<td>2'534</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>Estimated costs</td>
<td>Investment costs (IK)</td>
<td>40'000 [CHF]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Annual costs (JK)</td>
<td>3'467 [CHF / year]</td>
<td>3'467 [CHF / year]</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>Viability (ROI) (years)</td>
<td>5.7</td>
<td>5.7</td>
<td>Short-term measures</td>
</tr>
</tbody>
</table>
### 4.1.3 M7 Replace rotation regulator of primary air supply in furnace line 3

<table>
<thead>
<tr>
<th>M7</th>
<th>Primary air supply</th>
<th>Combustion line 3</th>
<th>Rotation regulator</th>
<th>Replace with FU controlled motors</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Measure</td>
<td></td>
<td>Existing regulator should be replaced with a new radial ventilator with FU control.</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>Evaluation</td>
<td></td>
<td>The existing air distribution system using a rotation regulator is outdated. With the new solution the specific energy requirement [kW/m^3/s] can be reduced to the comparable level of combustion line 4, P_{spec,O4} = 4.25 kW/m^3/s This results in a new energy requirement: P_{new} = P_{spec,O4} * V_{setp}, V_{setp} = 4.22 m^3/s</td>
<td></td>
</tr>
</tbody>
</table>

**Conclusion**

New solution permits more efficient primary air supply.

<table>
<thead>
<tr>
<th>C</th>
<th>Efficiency potential (electricity)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>in [kWh / year]</td>
<td>184'529</td>
</tr>
<tr>
<td></td>
<td>in [CHF p.a.]</td>
<td>11'994.00</td>
</tr>
</tbody>
</table>

Energy re-purchase tariff: 6.5 Rappen/kWh

#### 4.1.4 M16 Reduce operating pressure of flue gas rinsing system in furnace line 4

<table>
<thead>
<tr>
<th>M16</th>
<th>Flue gas extractor</th>
<th>Combustion line 4</th>
<th>Flue gas rinsing facility</th>
<th>Reduction of operating pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Measure</td>
<td></td>
<td></td>
<td>Set point for pressure drop via flue gas cleanser should be reduced as a trial.</td>
</tr>
<tr>
<td>B</td>
<td>Evaluation</td>
<td></td>
<td></td>
<td>Set point of counter-pressure is constantly 25 mbar. Mean power consumption of induced draught ventilator is 371 kW. If the comparable measure for combustion line 3 can be successfully implemented, the counter-pressure should be reduced by 10%.</td>
</tr>
</tbody>
</table>

**Conclusion**

If it proves feasible, this measure could result in increased efficiency.

<table>
<thead>
<tr>
<th>C</th>
<th>Efficiency potential (electricity)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>in [kWh / year]</td>
<td>324'996</td>
</tr>
<tr>
<td></td>
<td>in [CHF p.a.]</td>
<td>21'125.00</td>
</tr>
</tbody>
</table>

Energy re-purchase tariff: 6.5 Rappen/kWh

#### Estimated costs

- **Investment costs (IK)** in [CHF]: 45'000.00
  - Adjustment of ring jet in flue gas cleanser (estimate)
- **Annual costs (JK)** in [CHF]: 3'900.00
  - IK = IK/a + IK/2 * z ; a = 15 years; z = 4%

**Viability (ROI) [years]**

- 2.2

Dependent measures

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**Compressed Air Systems I**

**Efficient Use of Electrical Motor Systems in Thermal Waste Plant**

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**Conference Proceedings**

**Volume II**

5–8 September 2005

Heidelberg Germany
4.1.5 M19 Reduce pump power requirement for cooling turbines

<table>
<thead>
<tr>
<th>A Measure</th>
<th>During the cooler months, cooling of turbine groups 1 and 2 should be secured with the aid of only one cold water pump.</th>
</tr>
</thead>
<tbody>
<tr>
<td>B Evaluation</td>
<td>During the summer, the river temperature is too warm for cooling with only one pump. Mean power consumption of cold water pumps is 122 kW and 130 kW respectively. During 7 months of the year, operation can be secured through hydraulic switching with one cold water pump.</td>
</tr>
</tbody>
</table>

Conclusion | This measure results in a significant increase in efficiency without the need for investment. |

<table>
<thead>
<tr>
<th>C Efficiency potential (electricity)</th>
<th>( P_{\text{mess}} = 252 \text{ kW} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>in [kWh/year]</td>
<td>643'860</td>
</tr>
<tr>
<td>in [CHF p.a.]</td>
<td>41'851.00</td>
</tr>
<tr>
<td>Energy re-purchase tariff: 6.5 Rappen/kWh</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>D Estimated costs</th>
<th>Investment costs (IK) in [CHF] 0.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual costs (JK) in [CHF p.a.]</td>
<td>0.00</td>
</tr>
<tr>
<td>( \text{JK} = \text{IK}/a + \text{IK}/2 \cdot z ); ( a = 15 \text{ years}; z = 4% )</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>E Viability (ROI) [years]</th>
<th>&lt; 1.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Realised measures</td>
<td></td>
</tr>
</tbody>
</table>

4.1.6 M21 Reduce air exchange in turbine hall

<table>
<thead>
<tr>
<th>A Measure</th>
<th>Turbine hall, including basement and sound-proofing, should be ventilated on a temperature control basis and with periodical flushing.</th>
</tr>
</thead>
<tbody>
<tr>
<td>B Evaluation</td>
<td>For air supply purposes in the turbine hall, some monoblocs can be eliminated and replaced by simple apertures in the façade. Adequate aeration can be secured by carrying out a 30-minute flushing procedure every 12 hours. The hall should be ventilated permanently when temperatures are &gt; 40°C.</td>
</tr>
</tbody>
</table>

Conclusion | The halls concerned can be ventilated much more efficiently. |

<table>
<thead>
<tr>
<th>C Efficiency potential (electricity)</th>
<th>( \Delta E = \Delta P \cdot t ); ( \Delta P = P_{\text{mess}} / 2 ); ( t = 5110 \text{ h} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>in [kWh p.a.]</td>
<td>150'000.00</td>
</tr>
<tr>
<td>in [CHF p.a.]</td>
<td>9'750.00</td>
</tr>
<tr>
<td>Energy re-purchase tariff: 6.5 Rappen/kWh</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>D Estimated costs</th>
<th>Investment costs (IK) in [CHF] 20'000.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual costs (JK) in [CHF p.a.]</td>
<td>1'733.00</td>
</tr>
<tr>
<td>( \text{JK} = \text{IK}/a + \text{IK}/2 \cdot z ); ( a = 15 \text{ years}; z = 4% )</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>E Viability (ROI) [years]</th>
<th>2.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Immediate measures</td>
<td></td>
</tr>
</tbody>
</table>
4.2 Overall evaluation of measures

If all potential measures relating to electricity consumption were to be implemented in Turgi waste treatment plant, this would result in maximum energy savings of 2.2 GWh.

Table 5: Maximum realisable measures relating to electricity

<table>
<thead>
<tr>
<th>Maximum realisable measures</th>
<th>Utilisation</th>
<th>Savings</th>
<th>Costs</th>
<th>Viability</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[Yrs]</td>
<td>[kWh p.a.]</td>
<td>[CHF p.a.]</td>
<td>[CHF]</td>
</tr>
<tr>
<td>Pos</td>
<td>Description</td>
<td>Electricity</td>
<td>Gross yield</td>
<td>Investments</td>
</tr>
<tr>
<td>TOTAL</td>
<td>Immediate measures</td>
<td>14.8</td>
<td>296'040</td>
<td>19'244.00</td>
</tr>
<tr>
<td>TOTAL</td>
<td>Short-term measures</td>
<td>15.6</td>
<td>738'141</td>
<td>47'979.00</td>
</tr>
<tr>
<td>TOTAL</td>
<td>Dependent measures</td>
<td>14.5</td>
<td>481'800</td>
<td>31'317.00</td>
</tr>
<tr>
<td>TOTAL</td>
<td>Realised measures</td>
<td>15.0</td>
<td>643'860</td>
<td>41'851.00</td>
</tr>
<tr>
<td>TOTAL</td>
<td>Maximum possible measures</td>
<td>15.0</td>
<td>2'159'841</td>
<td>140'391.00</td>
</tr>
</tbody>
</table>

The measures would trigger investments totalling 229,000 Swiss francs, and result in an annual yield of 121,000 Swiss francs. The average return of investment would be 1.7 years with an expected mean service life of 15 years.

Without the dependent measures which can only be implemented under certain conditions, we are left with minimum realisable measures which would trigger investments totalling 184,000 Swiss francs, and result in an annual yield of 93,000 Swiss francs. The average return of investment for these measures would also be 1.7 years with an expected mean service life of 15 years.

With own consumption amounting to approx. 17 GWh, the potential savings thanks to the implementation of these measures would be a minimum of 1.7 GWh or a maximum of 2.2 GWh. This is equivalent to a reduction in own consumption by between 10 (minimum) and 13 (maximum) percent.
5 Assessment of potential efficiency increase in all Swiss waste treatment plants

The plant’s own consumption before optimisation was 17 GWh. With a processed volume of 113,900 tonnes, the resulting specific own consumption is 149 kWh/tonne.

Table 6: Results for Turgi waste treatment plant

<table>
<thead>
<tr>
<th>Canton</th>
<th>Name</th>
<th>Waste vol.</th>
<th>No. of Waste lines</th>
<th>Production in 2002</th>
<th>Own electricity requirement</th>
<th>Efficiency potential</th>
<th>Specific</th>
<th>Proportional</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aargau</td>
<td>Turgi waste treatment plant</td>
<td>113'900</td>
<td>2</td>
<td>85'000</td>
<td>17'000</td>
<td>149</td>
<td>132</td>
<td>11%</td>
</tr>
</tbody>
</table>

*Absolute target = mathematical average (minimum, maximum savings)

The measures result in an annual energy saving of between 1.7 GWh (minimum) and 2.2 GWh (maximum). The resulting target is a mean specific energy consumption of 123 kWh/tonne of waste. After implementation of the optimisation measures, Turgi can be operated with a specific electricity consumption of 132 kWh/tonne of waste.

Switzerland’s 31 waste treatment plants process a total of around 2.8 million tonnes of waste per annum. The total own electricity consumption of these plants is 410 GWh. The mean specific own electricity consumption is 148 kWh/tonne of waste.

If it were possible to reduce the mean specific own electricity consumption to the level of 132 kWh/tonne calculated in the Turgi case study, this would result in a total energy saving of 38 GWh, which is equivalent to the annual consumption of approximately 10,000 households.

Table 7: Estimated efficiency potential of all waste treatment plants in Switzerland

<table>
<thead>
<tr>
<th>Projection of efficiency potential</th>
<th>Waste Volume</th>
<th>Own electricity requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
<td>Waste Volume</td>
<td>Specific [kWh / t]</td>
</tr>
<tr>
<td>Current consumption levels of all treatment plants in Switzerland</td>
<td>2'815'663</td>
<td>148</td>
</tr>
<tr>
<td>Notified consumption levels of all treatment plants in Switzerland. Basis: Turgi case study</td>
<td>2'815'663</td>
<td>132</td>
</tr>
</tbody>
</table>

Efficiency potential

6 References

Complete report written in German can be downloaded from:

www.electricity-research.ch
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