Energy Efficient Electric Motors Systems

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Motor Systems Optimisation (MSO) USERs Training

This Manual is intended to provide introductory information in the area of Energy Efficient Electric Motors Systems, covering a variety of topics, ranging from tecnologies to policy and regulation, including references on the most recent developments.

The two-day MSO End Users Training is targeted to facility engineers, operators and maintenance staff of enterprises, equipment vendors and service providers and it is designed to teach how to assess motor systems, identify potential improvement opportunities and achieve cost savings through proper operation and controls, system maintenance, and appropriate uses of motor.

This two-day MSO End User Training is primarily designed to build or consolidate enterprise personnel's understanding of MSO and technical capacity for MSO oriented actions and to enable them to initiate the development and implementation of MSO measures and projects. The training is also intended to raise further interest in the UNIDO training and technical assistance offers.

List of Acronyms

AC	alternating current
BEP	best efficiency point
BHP	brake horsepower
BLDC	brushless DC (motor)
CDA	Copper Development Association
CEMEP	European Committee of Manufacturers of Electrical Machines and Power Electronics
CSA	Canadian Standards Association
DC	direct current
DOE	U.S. Department of Energy
EASA	Electrical Apparatus Service Association
EC	Electronically Commutated (motor)
EEM	Energy Efficient Motor
EERE	Office of Energy Efficiency and Renewable Energy
EMI	electromagnetic interference
EnPI	energy performance indicator
EISA	Energy Independence and Security Act of 2007
EPAct	Energy Policy Act of 1992
f	frequency in Hertz
HEM	High Efficiency Motor
Hz	hertz
hp	horsepower
I	amperage or current
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IGBT	insulated gate bipolar transistor
IM	induction motor
IP	ingress protection
ISO	International Organization for Standardization
kW	kilowatt
kWh	kilowatt-hour
LF	load factor
LCI	load-commutated inverter
mm	millimeters
MW	megawatt
NEMA	National Electrical Manufacturers Association
OEM	original equipment manufacturer
P	power
PF	power factor
PMSM	permanent magnet synchronous motor
PWM	pulse-width modulated
RMS	root-mean-square
rpm	rotations per minute
V	volt
VSI	voltage source inverter
VSD	variable speed drive
W	watt

1 Introduction

This manual gives a brief description of state-of-the-art technologies used to develop high efficiency motors, including premium efficiency induction motors, permanent magnet motors, and switched reluctance motors.

It also analyses issues that affect motor system efficiency and provides guidelines on how to deal with those issues namely by:

- Selection of energy-efficient motors
- Properly sizing of motors;
- Using Variable Speed Drives (VSDs), where appropriate. The use of VSDs can lead to better process control, less wear in the mechanical equipment, less acoustical noise, and significant energy savings;
- Optimisation of the complete system, including, the distribution network, power quality and efficient transmissions;
- Motor Systems Energy Assessments
- Taking Measurements
- Applying best maintenance practices.
- Motor Repair
- How to win approval for energy efficiency projects
- Energy Management Systems

An updated overview of worldwide energy performance standards and programs to promote high efficient electric motors is given.

2 High Energy Efficient Motor Technologies

Energy efficiency of electric motors has been a growing concern both for manufacturers and end-users in last couple of decades. Some effort has been put into developing new ways to increase three-phase induction motors efficiency and other technological solutions are emerging which can lead to even higher efficiency levels. A brief description of these very efficient technological solutions is given in this section.

2.1 Induction Motor basics

The vast majority of the motors used in industry are squirrel-cage induction motors (Figure 1 and Figure 3) due to their low cost, high reliability and fairly high efficiency. There are no electrical connections to the rotor, which means that there are no brushes, commutator or slip rings to maintain and replace.

The speed of an induction motor is essentially determined by the frequency of the power supply and by the number of poles of the motor.

$$synchronous\ \ speed\ [rpm] = \frac{frequency\ of\ the\ applied\ voltage\ [Hz] \times 60}{number\ of\ pole\ pairs}$$

$$synchronous\ \ speed\ [rad/s] = \frac{2\pi\ \times frequency\ of\ the\ applied\ voltage\ [Hz]}{number\ of\ pole\ pairs}$$

$$slip\ [\%] = \frac{Synchronous\ speed - running\ speed}{Synchronous\ speed} \times 100$$

However, the speed decreases a few percent when the motor goes from no-load to full load operation (Figure 2).

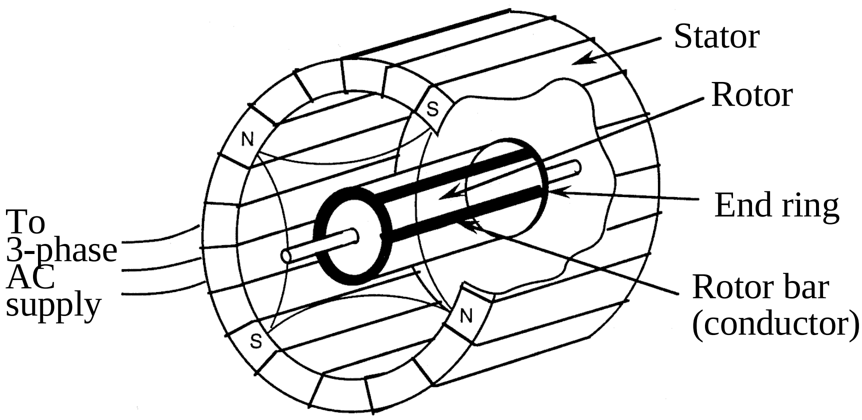


Figure 1 Diagram of Squirrel Cage Induction Motor

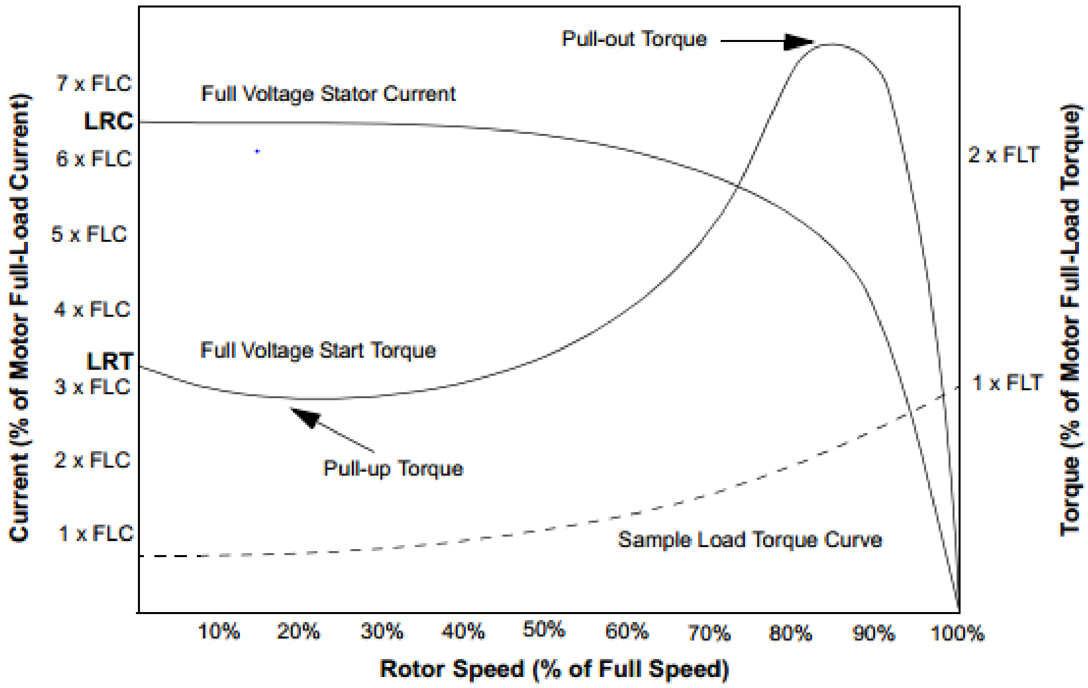


Figure 2 Typical Torque-Speed Curve of a 3-phase AC Induction Motor

Where:

LRC *- Locked Rotor Current (Starting Current),* ***LRT****- Locked Rotor Torque (Starting Torque)*

FLC*- Full Load Current,* ***FLT****- Full Load Torque*

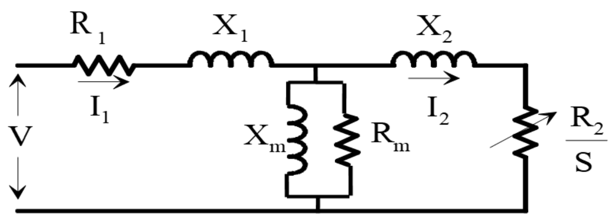


Figure 3 Squirrel Cage Induction Motor Equivalent Circuit

Where:

R1, R2 = Stator and Rotor Resistance;

X1, X2 = Stator and Rotor Leakage Reactance;

Xm = Magnetising Reactance;

Rm = Magnetising Resistance;

ω_s *= Synchronous Speed (rad/s);*

ω_{rotor} *= Rotor Speed (rad/s)*

S = Slip = $(\omega_s - \omega_{rotor}) / \omega_s$

Induction motors main characteristics are:

- Low construction complexity
- High reliability (no brush wear), even at very high achievable speeds
- Medium efficiency at low power (typically below 2.2. kW), high efficiency at high power
- Driven directly by the grid or by multi-phase inverter speed controllers
- Low Electro-Magnetic Interference (EMI)
- Sensorless speed control is possible
- Lowest cost per kW among different motor technologies

2.2 Energy Efficient Induction Motors

Motor Efficiency is generally defined as:

$$Efficiency = \frac{Output\ mechanical\ power}{Input\ electrical\ power}$$

The difference between the output mechanical power and the input electrical power is due to five different kinds of losses occurring in a machine: electrical losses, magnetic losses, mechanical losses and stray load losses, and in the case of brushed motors, the brush contact losses.

- **Electrical losses** (also called Joule losses) are expressed by I^2R, and consequently increase rapidly with the motor load. Electrical losses appear as heat generated by electric resistance to current flowing in the stator windings and in the rotor conductor bars and end rings.

- **Magnetic losses** occur in the steel laminations of the stator and rotor. They are due to hysteresis and eddy currents, increasing approximately with the square of the magnetic flux-density.

- **Mechanical losses** are due to friction in the bearings, ventilation and windage losses.

- **Stray load losses** are due to magnetic flux leakage, harmonics of the air gap magnetic flux density, non-uniform and inter-bar currents distribution, mechanical imperfections in the air gap, and irregularities in the air gap magnetic flux density.

As an example, Figure 4 shows the distribution of the induction motor losses.

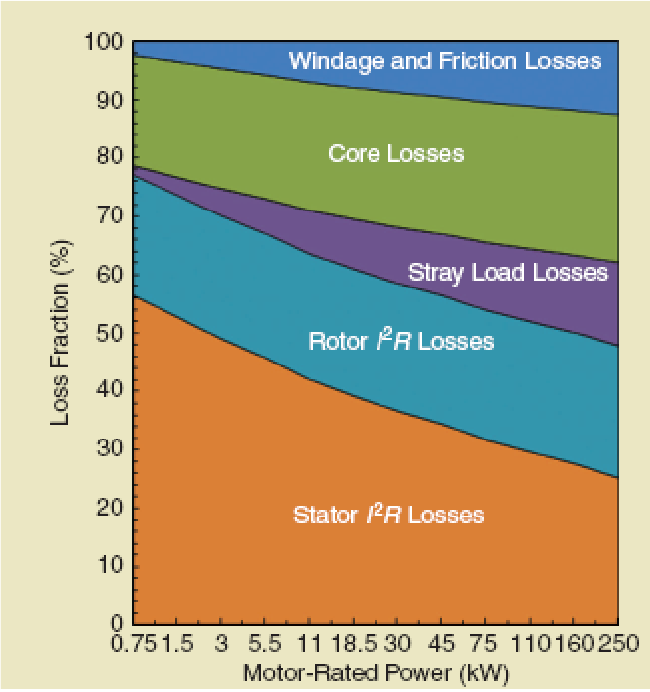


Figure 4.Typical fraction of losses in 50-Hz, four-pole IMs [1]

The most efficient induction motors available in the world market today have efficiency levels above the IE4 minimum requirements. This represents a decrease in losses of about 15% in relation to the high efficiency motors (IE3 or Nema Premium) available in the market.

High efficiency motors are typically constructed with superior magnetic materials, larger magnetic circuits with thinner laminations, larger copper/aluminium cross-section in the stator and rotor windings, tighter tolerances, better quality control and optimized design. These motors, therefore, have lower losses and improved efficiency. Because of lower losses the operating temperature can be lower, leading to improved reliability.

Some of the options to increase induction motors efficiency are presented in Figure 5.

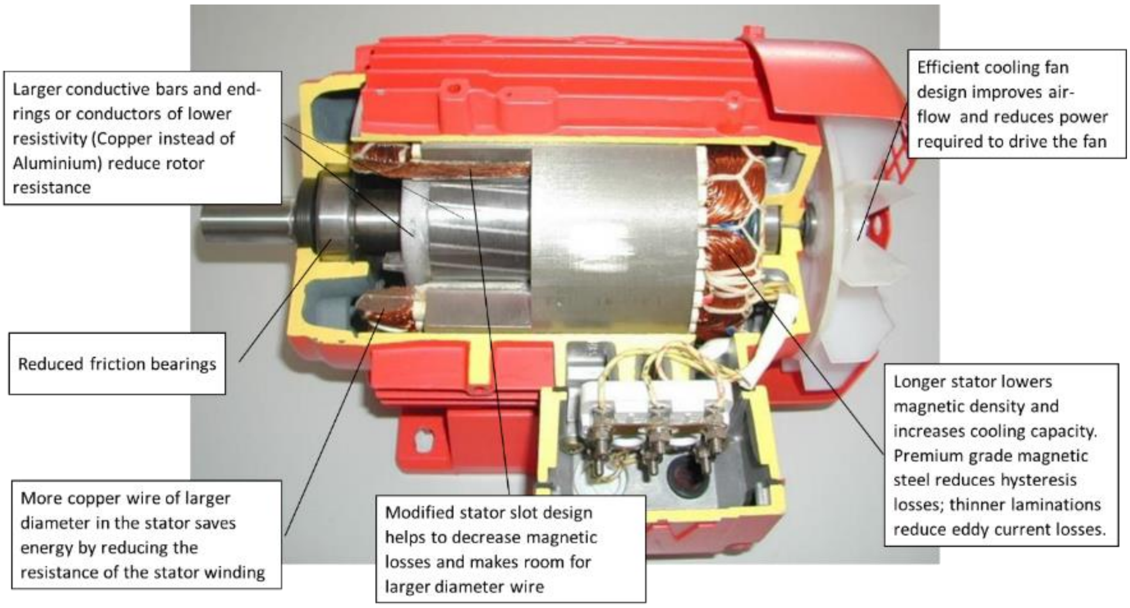


Figure 5 IE3 (also called NEMA Premium in North America) motor features.

Stator losses can be reduced by increasing the cross-section of stator windings which lowers their electrical resistance reducing I^2R losses. This modification is where the largest gains in efficiency are achieved. High efficiency motors typically contain about 20% more copper than standard efficiency models of equivalent size and rating.

Increasing the cross-section of the rotor conductors (conductor bars and end-plates) and/or increasing their conductivity (e.g. using copper instead of aluminium), and to a lesser extent by increasing the total flux across the air gap between rotor and stator reduces the rotor losses.

Magnetic core losses occur in the steel laminations of the stator and rotor and are mainly due to hysteresis effects and to induced eddy currents. Both types of losses approximately increase with the square of the magnetic flux density. Lengthening the lamination stack, which reduces the flux density within the stack, therefore reduces core losses. These losses can be further reduced through the use of magnetic steel with better magnetic properties (e.g. higher permeability and higher resistivity) in the laminations. Another means to reduce the eddy currents magnetic core losses is to reduce the laminations' thickness. Eddy current losses can also be reduced by ensuring adequate insulation between laminations, thus minimizing the flow of current (and I^2R losses) through the stack.

The additional materials used in order to improve efficiency can present themselves as a problem, as it may be difficult to meet the standard frame sizes especially in the low power range. Of course, this is not always the case since in many cases only the stator and rotor laminations are a little longer and this can be compensated in part by using a smaller fan, as the thermal losses to be dissipated are lower.

Figure 6 shows the relationship between power and shaft-height considering the different European and North-American standard frame sizes for 4-pole motors.

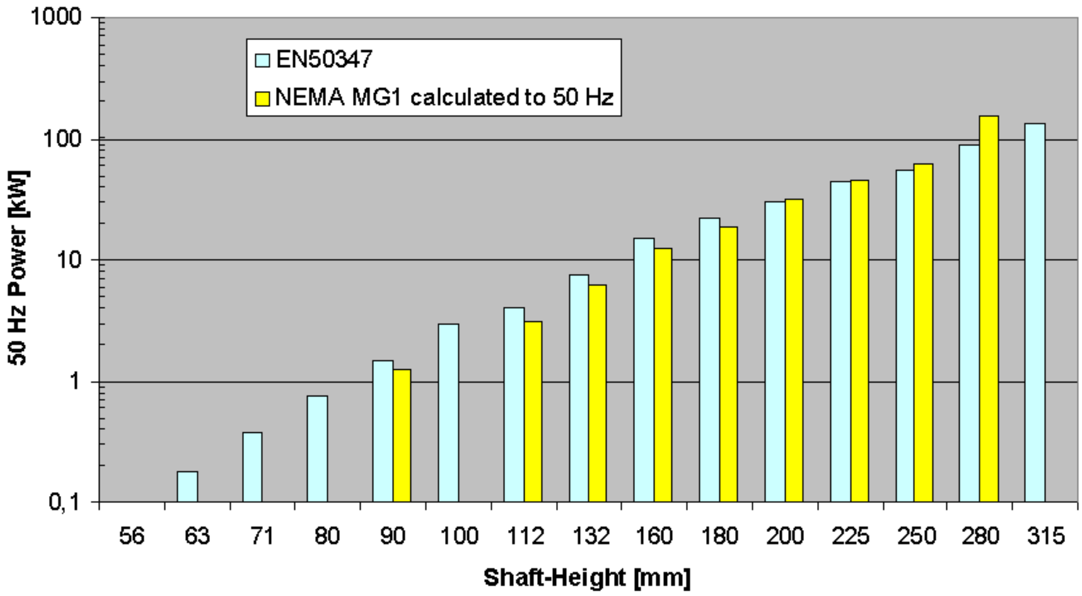


Figure 6. 4-Pole Output Power per Shaft-Height according to international standards EN50347 and NEMA MG1

The increase in materials also leads to higher rotor inertia in high-efficient motors which will contribute to extending the starting and reversing time in DOL motors or limit dynamic performance of the motor when it is controlled by a VSD.

Regarding the intermittent operation of high-efficiency motors, there are some cycling limits after which they lose their extra efficiency advantage. This is due to the extra starting losses/energy use over the typical duty cycle that may exceed the reduction of losses/energy in steady-state [2], as depicted in Figure 7.

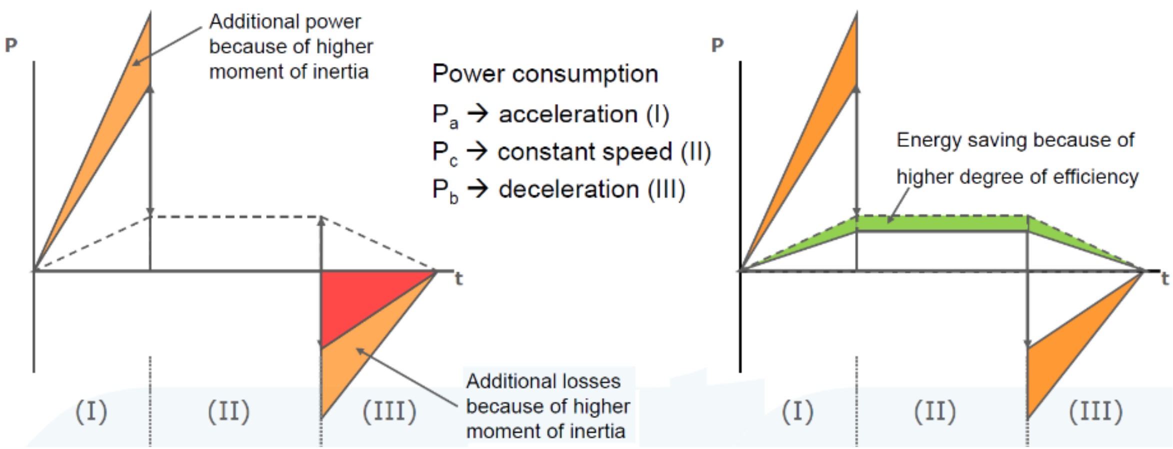


Figure 7 Losses in intermittent operation of induction motors [3]

One way to reduce I^2R losses is to substitute the aluminium conductor rotor bars with copper (Figure 8). Due to the excellent electrical conductivity of copper (57 MS/m compared to 37 MS/m for aluminium), replacing the aluminium in a rotor's conductor bars with die-cast copper can produce a significant improvement in the efficiency of an electrical motor. If this replacement is accompanied by a redesign of the motor that takes into account the higher conductivity of copper, even a greater efficiency improvement can be achieved, as shown in Figure 10.

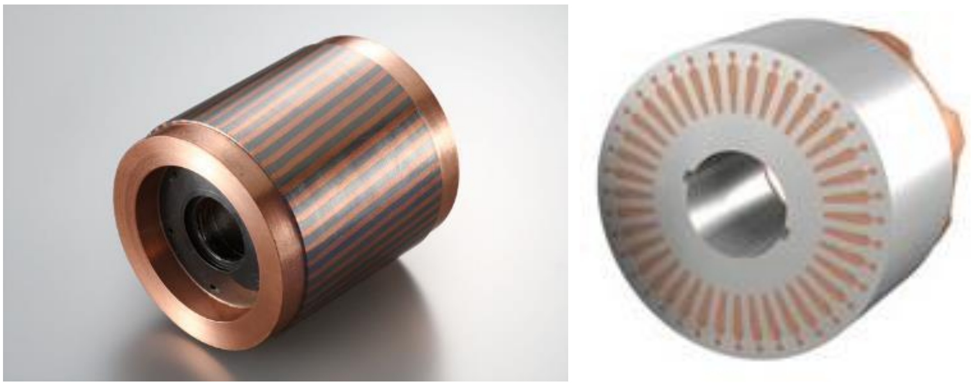


Figure 8 Copper rotor motor and a cut-away view (Source Copper Development Association)

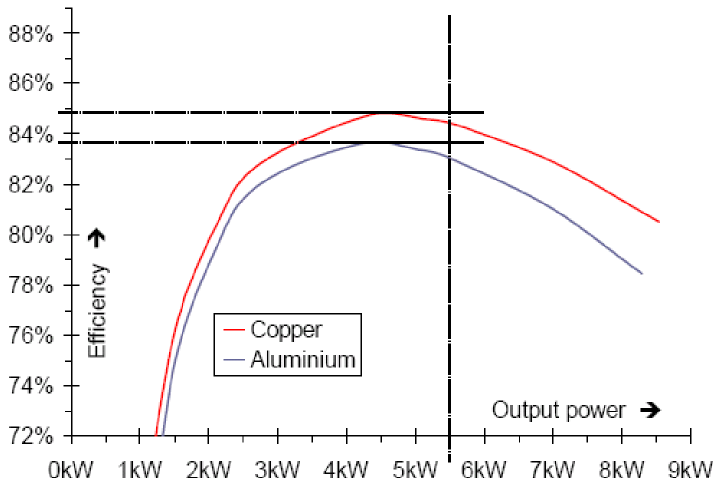


Figure 9. Comparison of the efficiency impact of an aluminium and copper rotor in an otherwise identical 5.5 kW motor [4]

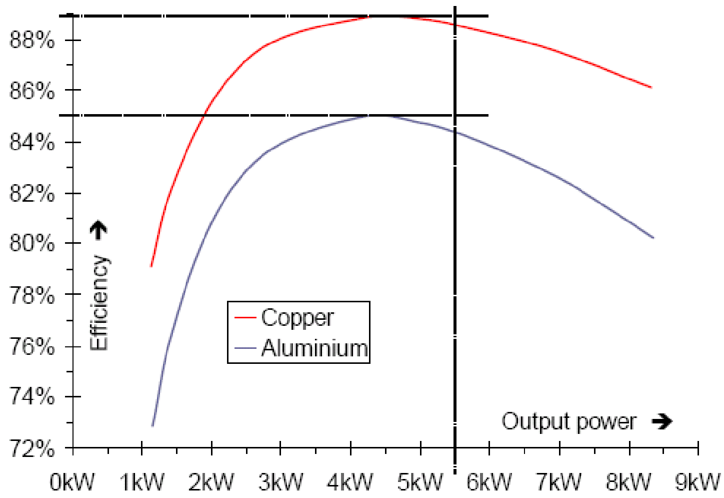


Figure 10. Comparison of the efficiency of an aluminium rotor motor and a copper rotor efficiency optimized 5.5 kW motor [4]

Because of the higher efficiency of the copper rotor, the length of the rotor, and therefore the motor, can be smaller than in an aluminium motor for the same power and efficiency rating. This can make possible to meet standard frame sizes with high efficiency motors, which would otherwise be difficult.

The higher melting point of copper (1083ºC versus 660ºC for aluminium) was initially a barrier in the large-scale production of copper die-cast rotors, due to the short lifetime of the dies. This problem has been successfully overcome and several manufacturers are now producing cost-effective copper rotor induction motors.

2.3 Permanent Magnet Motors

A Permanent Magnet Motor is a rotating electric machine where the stator is a classic three-phase stator like that of an induction motor and the rotor has permanent magnets which create the rotor magnetic field without incurring in excitation losses. Unlike a brushed DC motor, the commutation of motor without brushes is controlled electronically. These motors can be called:

- Permanent Magnet Synchronous Motors, also designated PMSM
- Electronically Commutated Motors also designated EC Motors
- Brushless DC motors, also designated BLDC motors

These motors typically require a frequency converter and some modells also require a rotor position sensor (encoder) for proper operation. In new sensorless designs the encoder can be replaced by a control algorithm in the converter. The AC supply is converted to a DC supply, which feeds a Pulse-Width Modulation (PWM) inverter, which generates an almost sinusoidal waveform, supplied to the stator windings. To rotate, the stator windings should be energized in a sequence to create a magnetic rotating field. It is important to know the rotor position in order to understand which winding will be energized following the energizing sequence.

Based on the required magnetic field density in the rotor, the proper magnetic material and geometry is chosen to make the rotor. Ferrite magnets have traditionally been used to make permanent magnets in low cost applications. As the technology advances and with decreasing costs, rare earth alloy magnets are gaining popularity. The ferrite magnets are less expensive, but they have the disadvantage of lower flux density for a given volume. In contrast, the alloy material has high magnetic density improving the size-to-weight ratio and give higher torque for the same size motor using ferrite magnets. Samarium Cobalt (SmCo) and the alloy of Neodymium, Iron and Boron (NdFeB) are some examples of rare earth alloy magnets used in high performance motors. Continuous research is going on to improve the flux density to compress the motor volume even further.

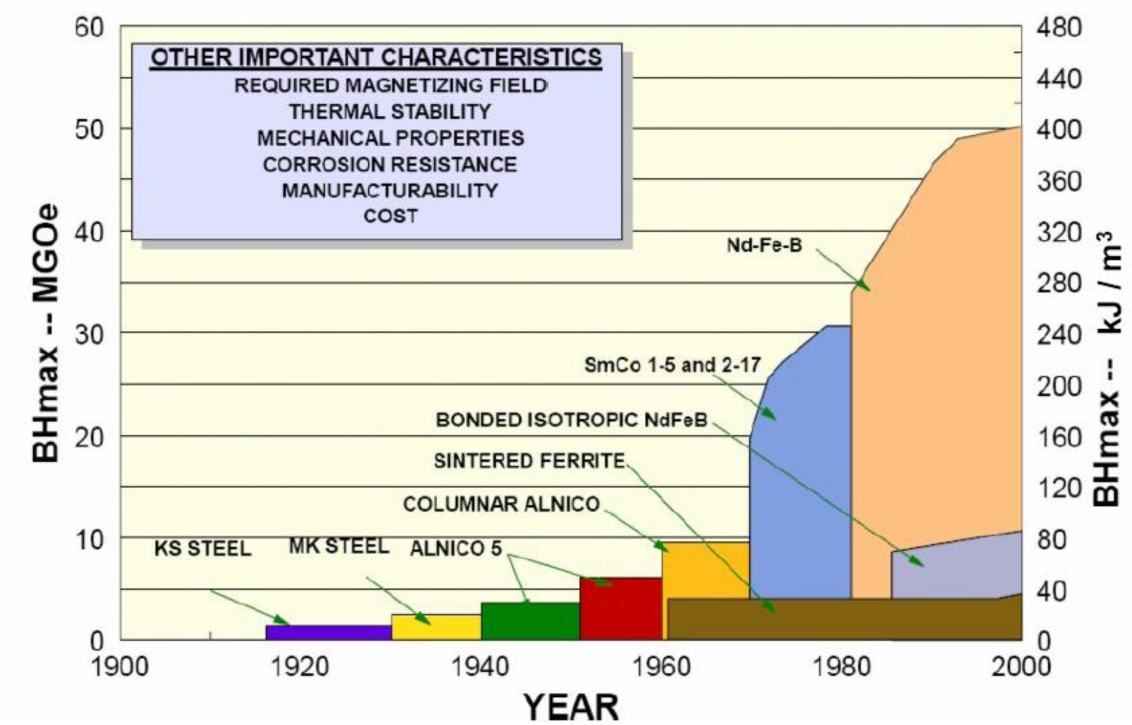


Figure 11. Advances in magnet energy product

This means the magnetic field generated by the stator and the magnetic field generated by the rotor, rotate at the same frequency. Permanent Magnet Motors do not experience the “slip” that is normally seen in induction motors.

Motors using permanent magnets are significantly more efficient than induction motors because they do not have the secondary windings in their rotors and because of synchronous operation, almost completely eliminating the rotor electric and magnetic losses.

In the low power range, and in applications requiring variable speed control, Permanent Magnet motors can lead to efficiency improvements of up to 10-15%, when compared with variable speed induction motors, as shown in Figure 12.

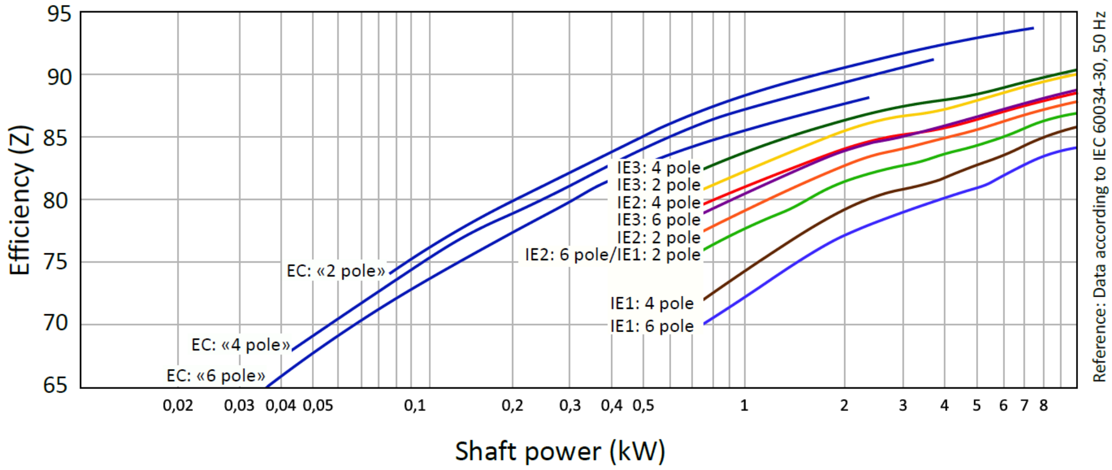


Figure 12 Efficiency of PMSM/EC/BLDC motors, compared with induction motors (Source EBM-Papst)

They also are much more efficient than brushed dc motors since they eliminate the excitation circuit losses.

Permanent Magnet Motors present a large savings potential and have been gaining market importance in some particular applications such as high performance motion control, in some types of variable speed fans and also in some high efficiency appliances (e.g. air conditioners).

Based on an innovative geometry for the motor rotor and stator, some motor manufacturers use much less costly ferrite magnets to deliver the performance level typically found in much more expensive rare earth-based permanent magnet motors

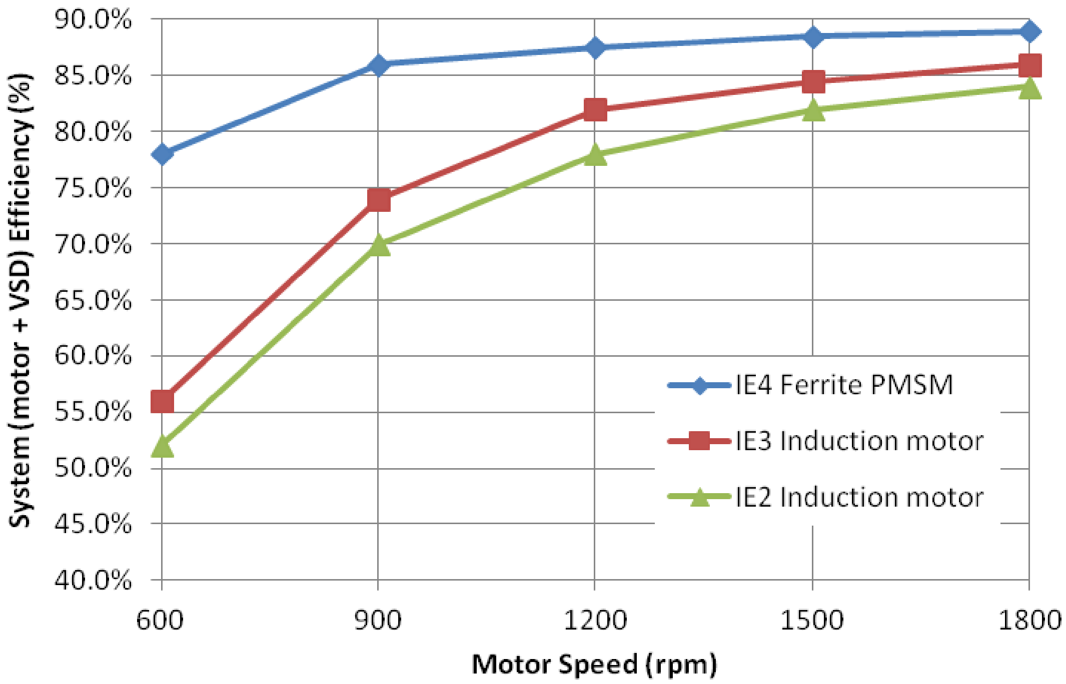
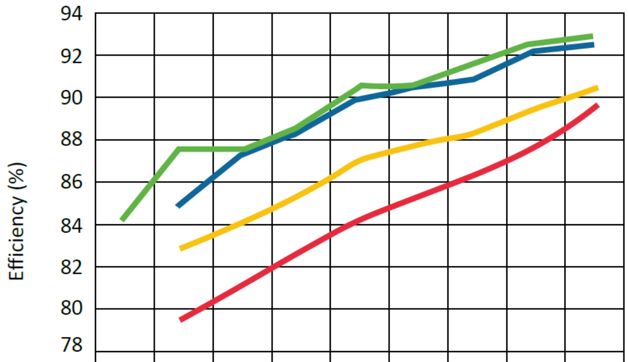


Figure 13 System Efficiency of ferrite magnet IE4 Super-Premium motor (NovaTorque) Vs. IE3/NEMA Premium and IE2 standard induction motors driven by a VSD

2.4 Line Start Permanent Magnet Motors

Another very high efficiency technology that has recently been introduced in the market by some manufacturers is the line start permanent magnet motor (LSPM). As the name implies the motor does not need an electronic controller, being able to start by direct connection to the mains supply. These motors have permanent magnets fitted in the induction motor squirrel cage rotor giving them the ability to start by direct coupling to an AC power source – and, therefore, avoiding the use of a Variable Speed Drive – whilst having very high efficiency during synchronous running.

To achieve very high efficiency levels (IE4 – Super Premium) high energy magnetic material such as NeFeB are used for the permanent magnets.



		80	80	L90S	90L	100L	100L	112M	132S	132M
	Frame	80	80	L90S	90L	100L	100L	112M	132S	132M
	Rated output (kW)	0,55	0,75	1,1	1,5	2,2	3,0	4,0	5,5	7,5
Efficiency	WQuatro	84,2	87,5	87,6	88,3	90,2	90,4	91,7	92,4	92,8
Efficiency	IEC IE4*		85,6	87,4	88,1	89,7	90,3	90,9	92,1	92,6
Efficiency	IEC IE3		82,5	84,1	85,3	86,7	87,7	88,6	89,6	90,4
Efficiency	IEC IE2		79,6	81,4	82,8	84,3	85,5	86,6	87,7	88,7

Figure 14. Efficiency of commercially available for IE4 Super-Premium motor LSPM motor (Source: WEG)

Since the motor operates as a synchronous machine, the induced currents in the rotor are much smaller than in an induction machine and, therefore, rotor joule losses are significantly reduced. In addition, it is possible to achieve unity-power-factor performance, thereby reducing the stator currents and the corresponding losses [5].

One of the main advantages of these “hybrid” motors is their interchangeability with induction motors. Their design enables them to keep the same output /frame ratio as standard induction motors in spite of having very high efficiency, and they do not require electronic motion control as do EC or PM machines since they are able to start from standstill with a fixed-frequency supply.

2.5 Switched Reluctance Motors

Switched Reluctance motors are very simple, robust and very reliable. They have a salient pole stator with concentrated excitation windings and a salient pole rotor with no conductors or permanent magnets. A coil is wound around each stator pole and is connected, usually in series with the coil on the diametrically opposite stator pole to form a phase winding.

The stator features straightforward laminated iron construction with simple coil windings: absence of phase overlaps significantly reduces the risk of inter-phase shorts. The compact and short coil overhangs make efficient use of active coil area (lower copper costs) [6].

Their operation is based on the principle that a salient poles rotor will move to a position of minimum reluctance to the flow of flux in a magnetic circuit. Since inductance is inversely proportional to reluctance, the inductance of a phase winding is maximum when the rotor is in the aligned position, and minimum when the rotor is in the nonaligned position. Therefore, energisation of a phase will cause the rotor to move into alignment with the stator poles, so minimizing the reluctance of the magnetic path.

Figure 15. Switched Reluctance Motor salient poles rotor and stator (source: Emerson)

Unlike induction motors, switched reluctance motors require a power converter circuit, controlling the on-off phase currents to produce continuous motion and torque. Rotor position feedback can be used to control phase energisation in an optimal way. Speed can be varied by changing the frequency of the phase current pulses while retaining synchronism with the rotor position.

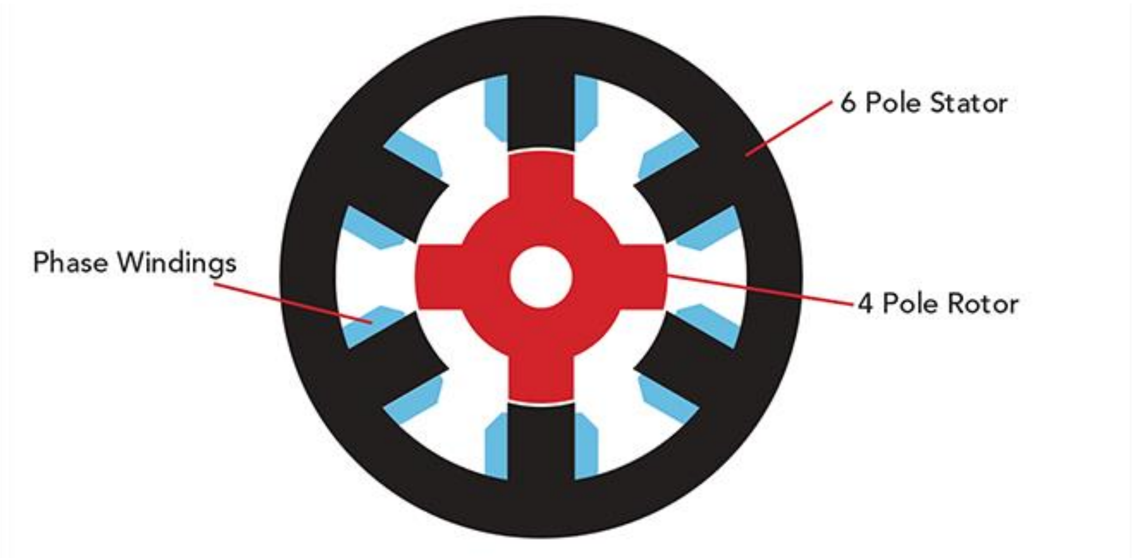


Figure 16. Typical design of 4 pole rotor Switched Reluctance Motor

The non-uniform nature of torque production leads to torque ripple and contributes to acoustic noise.

Switched Reluctance Motors typically have efficiencies of over 90%, including all motor and controller losses and its efficiency is maintained over a wide speed and load range.

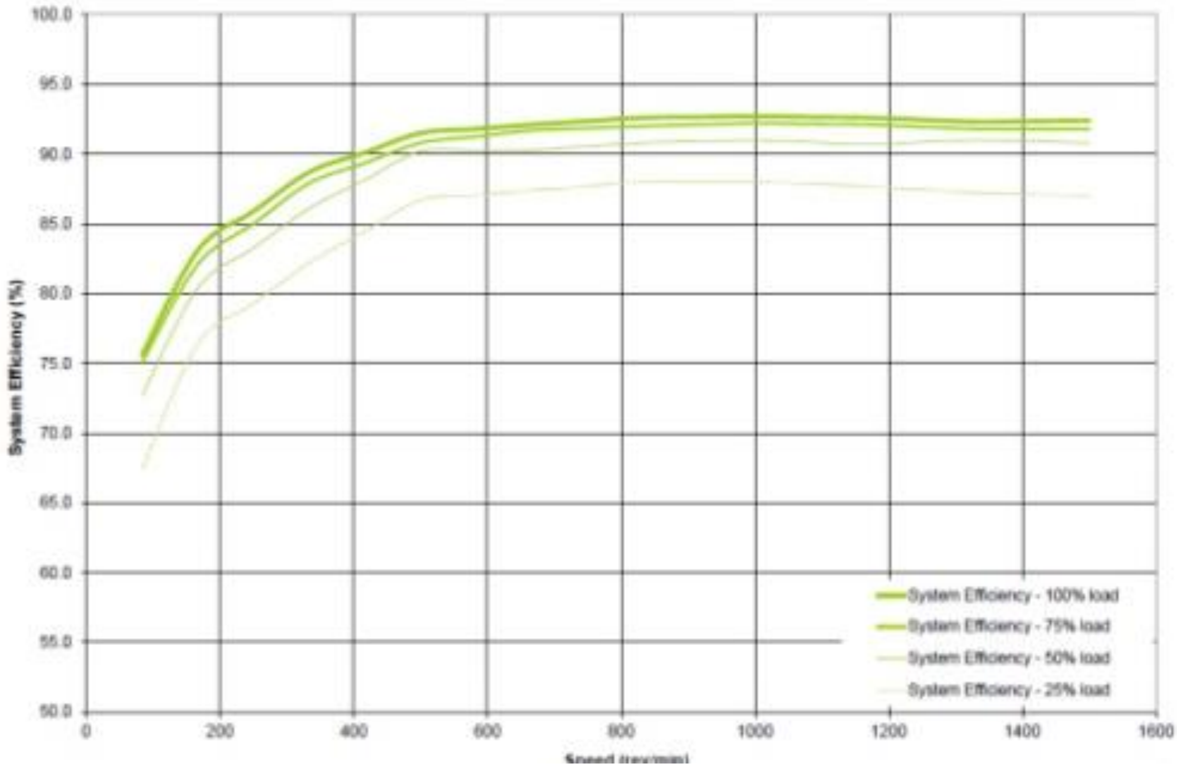


Figure 17. System effciency (Motor & Controller) Vs speed for a 44.5 kW Switched Reluctance Motor (Source: Nidec Motor Corporation)

2.6 Synchronous Reluctance Motors

Synchronous Reluctance Motors (SynRM) use a stator identical to that of induction motors and a rotor which has an equal number of poles as the stator. The rotor teeth are arranged to introduce internal flux “barriers,” holes which direct the magnetic flux along the so-called direct axis. Their operation is based on the principle that the rotor will move to a position of minimum reluctance to the flow of flux in a magnetic circuit.

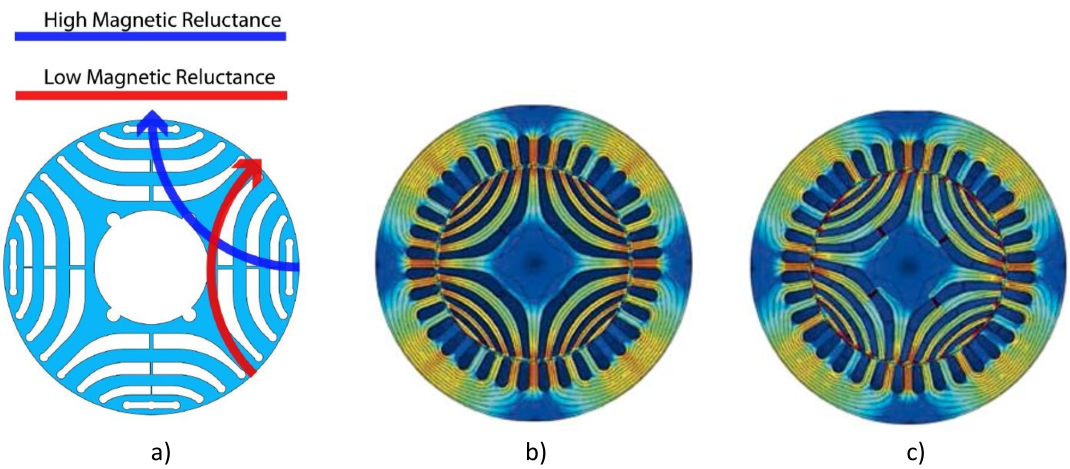


Figure 18. Synchronous Reluctance Motor Operating Principle a) rotor areas of high and low reluctance b)the rotor is aligned with the magnetic field so no torque is produced; c) the rotor is not aligned with the magnetic field and (counter-clockwise) torque is produced (Source: Oemer and ABB)

Since the rotor is operating at synchronous speed and there are no current-conducting parts in the rotor, rotor I^2R losses are avoided. Synchronous operation also means that the magnetic flux is almost constant in the rotor and, therefore, the rotor magnetic losses are negligible. Reduced rotor losses translate into very low winding temperatures and a cooler running motor, which increases the reliability and lifetime of the winding. Lower running temperature also means significantly lower bearing temperatures with a corresponding reduction in bearing failures (bearing failures cause about 70 percent of unplanned motor outages).

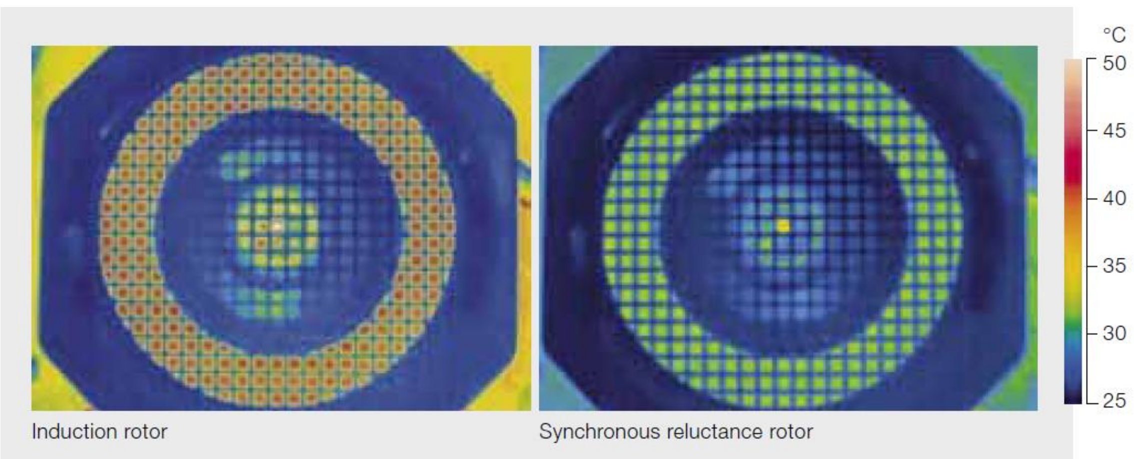


Figure 19. Thermal images of operating Induction motor and Synchronous Reluctance Motor (Source: ABB)

Unlike induction motors, synchronous reluctance motors cannot start directly on-line, requiring electronic control of the stator currents produce and ramp up the rotating magnetic field. Rotor position feedback may be used to control phase energisation in an optimal way.

Recent testing of the SynRM motor highlighted several key features of the motor in comparison to conventional induction motors, such as:

- Higher efficiency
- Simple rotor construction
- Lower temperature rise
- High power density
- Improved power factor

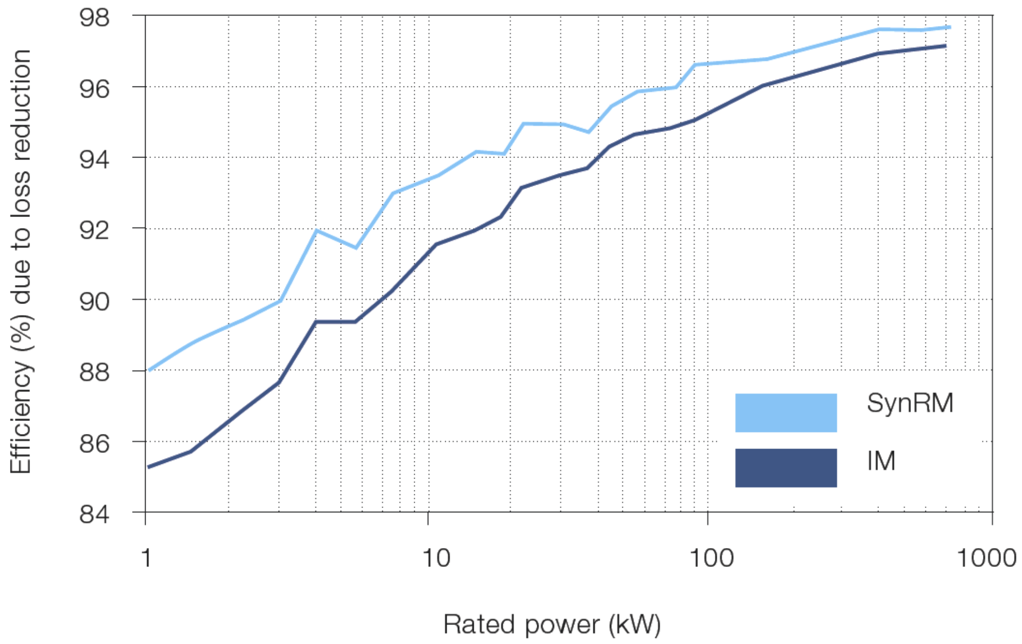


Figure 20 Potential efficiency increase due to rotor loss reduction in Synchornous Reluctance Motors (source:ABB)

The improved properties of these technologies can also be used to significantly reduce the overall size and weight of the motor, which in turn means that less materials are needed for its construction.

Figure 21 Pumping station using Synchornous Reluctance Motors (source:ABB)

Synchronous reluctance motor design are already available in the market reaching IE5 efficiency level performance, with costs similar to IE3 induction motors. This performance and cost makes this motor very competitive for variable speed application with significantly lower energy consumption when compared to commonly used IE2 induction motors (up to 50% reduction in losses).

3 Energy efficient motor systems

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
- Efficiency of the end-use device (e.g. fan, pump, etc.)

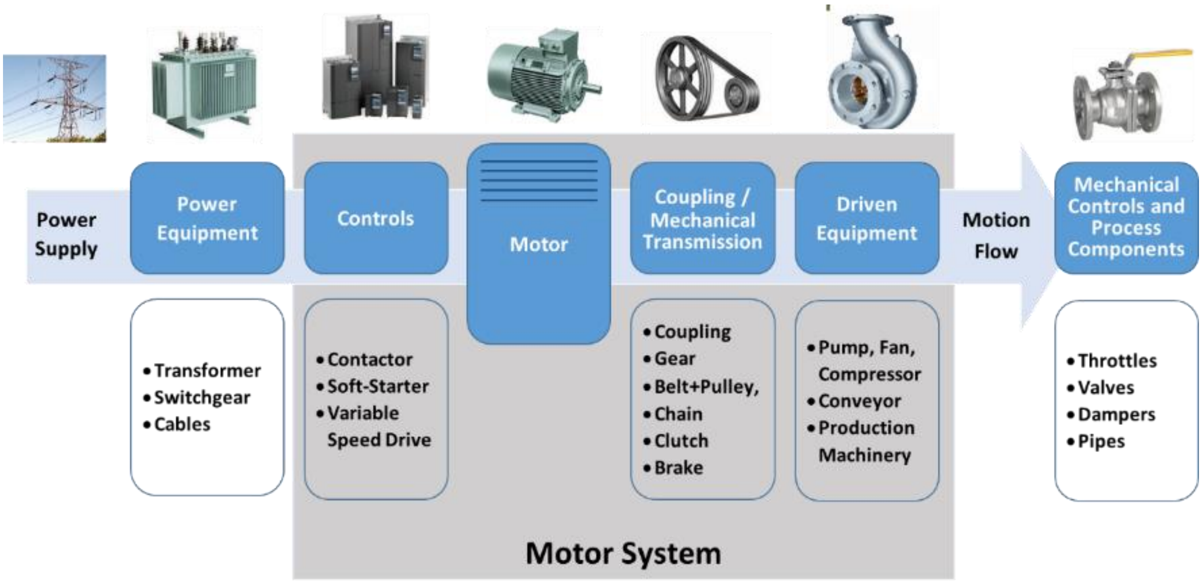


Figure 22 Motor system

It must be emphasised that the design of the process itself can also influence to a large extent the global efficiency (units produced/kWh).

A number of important but often overlooked factors which may affect the overall motor system efficiency include: power supply quality (high-quality power supply), careful attention to harmonics, system oversizing (proper equipment sizing), the distribution network that feeds the motor (attention to power factor and distribution losses), the transmission and mechanical components (optimised transmission systems), maintenance practices (careful maintenance of the entire motor system) and the match between the load and the motor (good load management practice), are discussed below.

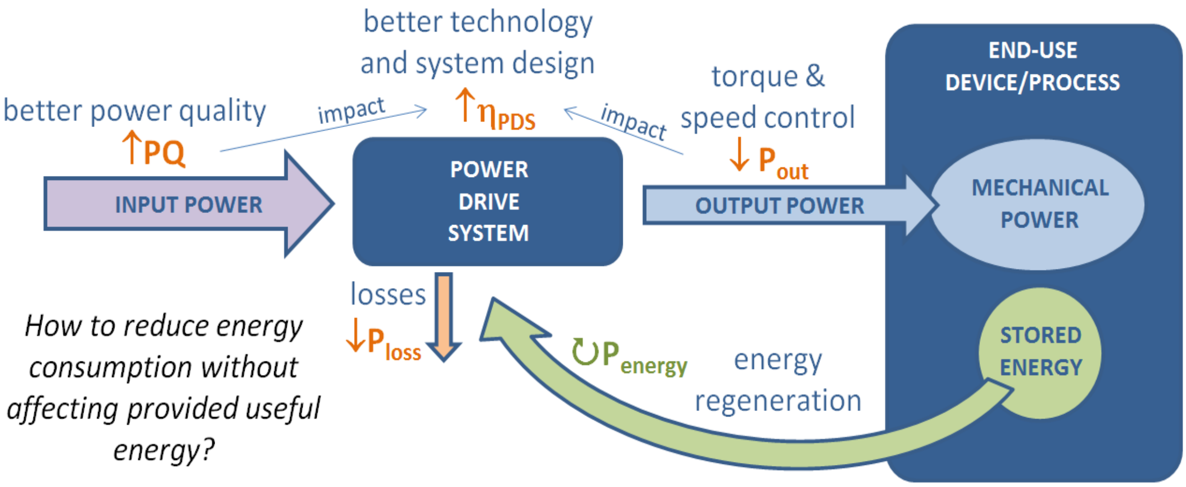


Figure 23 Strategies to reduce energy consumption in Electric Motor Systems [8]

In the design of motor systems it is essential to identify the mechanical load requirements (torque-speed characteristics) under a variety of operating conditions (e.g. starting, steady-state, variable load, etc.). With some loads (e.g. cranes, electric vehicles) it is possible to recover the stored energy (kinetic or potential energy) in the load.

3.1 Power Supply Quality

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. Such deviations include:

Voltage Unbalance

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.

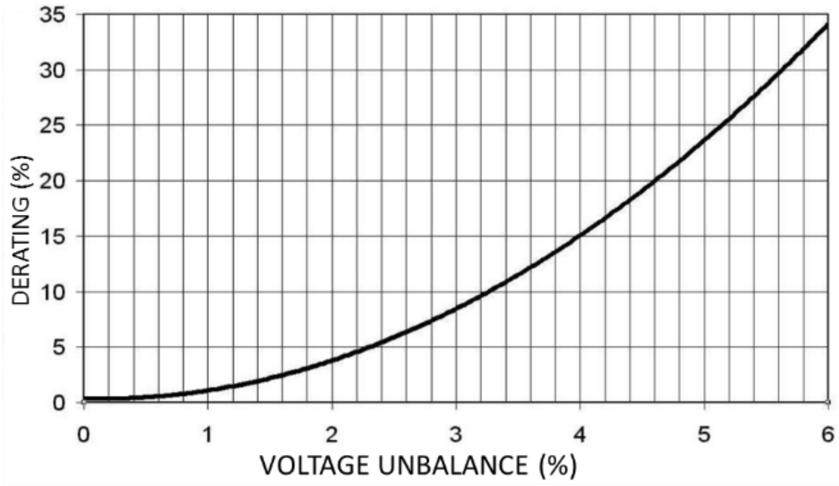


Figure 24 Effect of voltage unbalance on motor rating [10]

Undervoltage or Overvoltage

When the motor is running at or nearly full load, voltage fluctuations exceeding 10% can decrease motor efficiency, power factor and lifetime.

Harmonics

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. Harmonics can cause malfunctions in electronic equipment, including computers, induce errors in electric meters (one study sponsored by Electric Power Research Institute (EPRI) found measurement errors ranging from +5,9% to -0,8% in meters subjected to harmonics from VSDs), produce radio frequency static and destroy power system components.

3.2 Distribution Network

There are substantial losses through the distribution network from the substation to the loads. These losses can be reduced by proper selection and operation of efficient transformers, by correctly sizing the distribution cables and by correcting the power factor. In large industries it is also common to use a high distribution voltage to reduce the losses.

Transformers

Distribution transformers normally operate above 95% efficiency, unless they are old or are operating at very light load. Old, inefficient transformers should be replaced by new models that are more efficient. It is more efficient to run only one transformer at full load than to run two transformers at light load.

Cable Sizing

The currents supplied to the motors in any given installation will produce losses (of the I^2R type) in the distribution cables and transformers of the consumer. Correct sizing of the cables will not only allow a cost-effective minimisation of those losses, but also helps to decrease the voltage drop between the transformer and the motor. The use of the standard national codes for sizing conductors leads to cable sizes that prevent overheating and allow adequate starting current to the motors, but can be far from being an energy efficient design. Ideally the cables should be sized not only taking into consideration the national codes, but also considering the life-cycle cost.

In general, in new installations it is cost-effective to install a larger cable than that required by code, if the larger cable can be installed without increasing the size of the conduit, the motors operate at or near full load, and the system operate a large number of hours per year.

Power Factor Compensation

A poor power factor means higher losses in the cables and transformers, reduced available capacity of transformers, circuit breakers, and cables, and higher voltage drops.

In the case of motors, the power factor is maximum at full load, and it decreases with the load.

As discussed in section 3.3 an oversized motor will significantly drop the power factor. Thus, a properly sized motor will improve the power factor. Low power factor can be corrected by using capacitors connected to the motor or at the distribution transformer. Reactive power compensation not only reduces the losses in the network but also allows full use of the power capacity of the power system components. Additionally, the voltage fluctuations are reduced, thus helping the motor to operate closer to the voltage for which it was designed.

3.3 Motor oversizing

Studies on the use of electric motors in the European countries highlighted that the average motors working load is far below the rated motor power. The average load factor among all surveyed sectors (foods, paper, chemicals, ceramics, foundries and steel, tertiary sector) was estimated to range from 41% for small size motors (below 4 kW) to 51% for motors above 500 kW. In some sectors (foods, tertiary) the average working load is even lower, with a minimum of 24% for smaller motors.

The reasons why designers tend to oversize the motors are usually due to the aim of improving:

- the system reliability
- the starting torque
- the ability to accommodate increasing power requirements
- the allowance for higher load fluctuations
- the operation under adverse conditions (like voltage unbalance or undervoltage)
- the inventory of spare motors

3.3.1 The effects of oversizing

The general practice of motors over sizing is a confirmation that the energy performances (minimum losses in motors and supply lines) are often overlooked in the industry. The machinery manufacturers, who are responsible for choosing the motor in the first place, as well as the users who should influence the buying phase or the replacement of broken down motors, should consider that the design criteria leading to over sizing may have strong consequences on the energy bill.

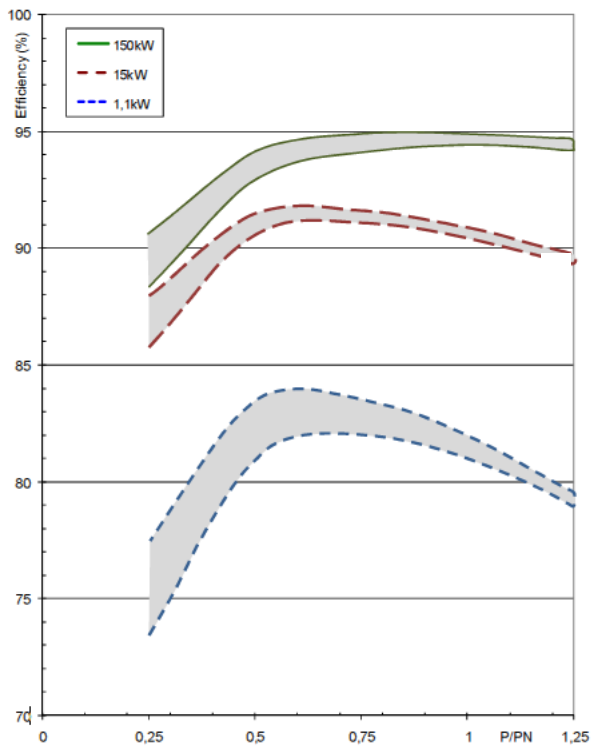


Figure 25 Motor Efficiency vs. Load [11]

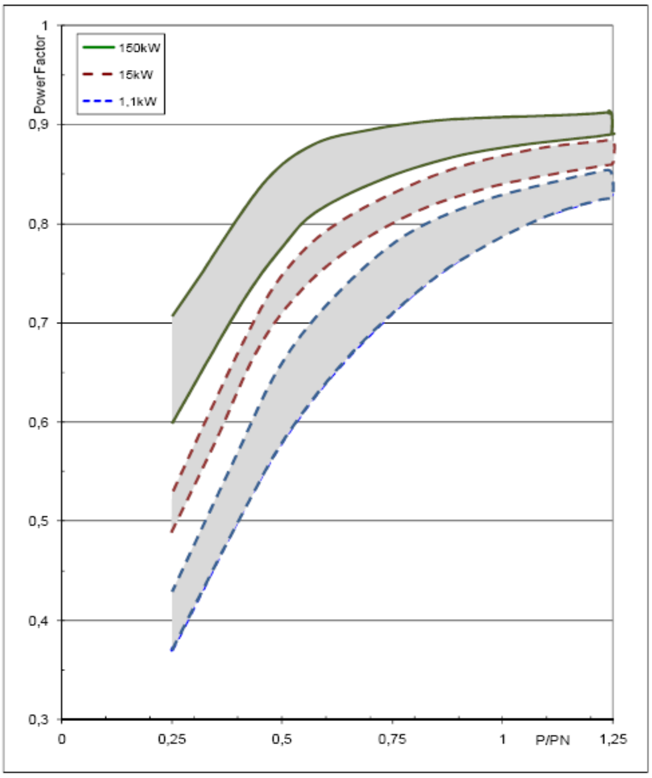


Figure 26 Power Factor vs. Load [11]

Whenever a motor has a working point far below 100% of rated power, its efficiency and power factor decrease as well as the capital cost increases.

In most motors the efficiency is almost constant from 75% to full load, but it drops significantly below 50% of full load. This effect is more evident for small motors. Figure 25 shows the efficiency vs. load factor of different power electric motors

The comparison of the efficiency characteristics between standard and energy-efficient motors (EEM) shows that even the benefits of using EEM's may be wasted if the load factor is abnormally low.

The adverse effect of the reduction of power factor due to over sizing is often neglected. Figure 26 shows the power factor vs. load factor of electric motors.

Unless the reactive power is compensated for each motor, the additional line losses due to over sizing may, in some cases, be a key factor for the proper motor selection.

3.3.2 Recommended procedure for motor selection

Technical fundamentals and practical rules for accurate motor sizing are available to electrical engineers. A detailed procedure, taking into account all major parameters influencing the optimization of the motor selection, is outlined below.

The application of the procedure shows that the available alternatives (different motors types and sizes) for an application may produce significantly different consequences in terms of energy consumption and economic profitability. The selection of a motor working with a high load factor is usually recommended, but a general statement in that sense cannot be made. Firstly, the reasons for over sizing the motor systems, as listed above, are sound, and must be taken into account to some extent. Second, the losses and costs associated with a specific application vary widely depending on the size and make of the motor, as related to the load and motor mechanical characteristics. In a number of cases the improved efficiency of bigger motors may override the additional losses due to a lower load factor.

That is why the design of the new motor applications or motor substitution should always be based on specific calculations. The adoption of rule-of-thumb decisions should be avoided, as they may unexpectedly lead to excessive energy waste.

The expected potential savings, of electric energy that might be obtained free of charge just by a careful motor sizing, are not less than 2% of the motor consumption.

One particularly useful motor selection software is the **Motor Systems Tool**[1], developed by the Electric Motor Systems Annex of the IEA Technology Collaboration Programme on Energy Efficient End-Use Equipment (4E). It enables the user to simulate a full motor system from power supply to application. From one known duty point all partials are calculated as well as the total system efficiency. Any change in speed, load or components is calculated dynamically and results are presented instantly.

Figure 27 summarizes the motor selection process flow, which is detailed below.

[1] The tool can be freely downloaded at: https://www.motorsystems.org/motor-systems-tool

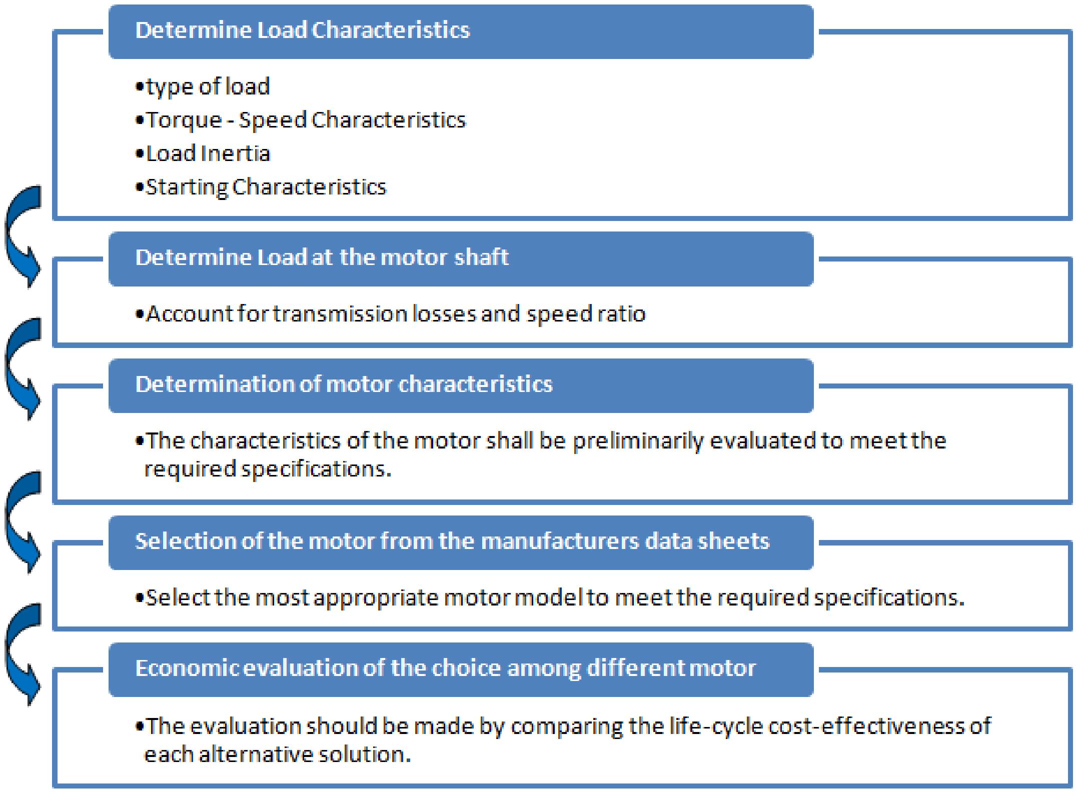


Figure 27 Motor selection process flow

Definition of the type and characteristics data of the load

The following load characteristics shall be defined:

- type of load (short description of the operating machine);
- rotation speed required by the load in normal working conditions;
- power or torque (constant torque, quadratic torque, decreasing torque) required by the load at the above speed;
- moment of inertia of the load;
- mechanical characteristic (torque-speed) of the load; the values of torque at 75%, 50%, 25% of rated speed are recommended;
- starting time required by the load;
- starting torque to be applied to the load (may be computed from the starting time, the load inertia and the rated speed);
- ratio starting torque to rated torque;
- anticipated overloads and their duration;
- type of mechanical coupling;
- speed ratio r (load shaft /motor shaft speed): this ratio may imply the choice of the number of poles;
- coupling efficiency

Mechanical data transfer from the load to the motor shaft

The mechanical data shall be transferred to the motor shaft via the r ratio defined above:

- rotation speed and moment of inertia;
- adjusted power to account for the transmission losses;
- adjusted torque to account for the transmission efficiency and speed ratio r;
- the starting time is unchanged.

Preliminary evaluation of the motor rating

The characteristics of the motor shall be preliminarily evaluated, to be compared later with the motors available in the market (number of poles, power):

- rated speed and power: they are assumed to be the same as the load values transferred to the motor shaft;
- supply frequency:
- the rated slip is assumed to have the typical value for the motors having the required power range;
- the synchronous speed and the number of poles is computed accordingly;
- if the number of pole pairs is close to an integer, the motor selection may be made by means of the manufacturers technical sheets; if it is not the case the speed ratio r shall be adjusted until an integer number of pole pairs is obtained.

Selection of the motor from the manufacturers data sheets

The manufacturers data sheets shall be searched to find the motor the characteristics of which show the best fit with the preliminary calculations.

If wider safety margins are sought, the process may be repeated selecting motors with higher performance. The procedure is the following:

- the number of pole pairs is set to the value arising from the preliminary calculation;
- the motor having rated power close to the one computed and a torque characteristic (maximum to rated and locked rotor to rated torque ratios) that matches with the application requirement;
- the motor rated speed and slip are found in the data sheet;
- the motor torque data, like maximum and starting torque are found in the data sheet, and their consistency with the operating conditions (starting time, overload capability) and the rated torque shall be checked;
- the torque values at different loads, that is the mechanical motor characteristic, are also usually provided by the manufacturer;

- the values of rated efficiency and power factor shall be determined accordingly.

Identification of the working point as the intersection of the load and motor characteristics

When the motor is selected, the following procedure applies:

- the working point (torque and speed) shall be determined: this may be made either graphically (plotting the motor and load torque-speed characteristics), or analytically (linearizing the two characteristics in the neighbourhood of the working point);

the following parameters at the working point may now be calculated:

- speed and slip;
- motor output power;
- load factor (the ratio of the output power to the rated output power);
- motor efficiency, either on the basis of the manufacturers data or average data relevant to a load equal to 100%, 75%, 50%, 25% of rated power;
- motor input power (the ratio of the output power to the efficiency);
- power factor;
- motor losses;
- line losses.

Economic evaluation of the choice among different motor

The evaluation should be made by comparing the cost-effectiveness of each alternative solution, having regard to both the cost of the motors and the anticipated yearly savings on the energy bill.

3.4 Transmission System

The transmission system transfers the mechanical power from the motor to the final end-use. The choice of transmission is dependent upon many factors, namely: the desired speed ratio, motor power, layout of the shafts, type of mechanical load, etc. The most important kind of transmission types available include: direct shaft couplings, gearboxes, chains and belts.

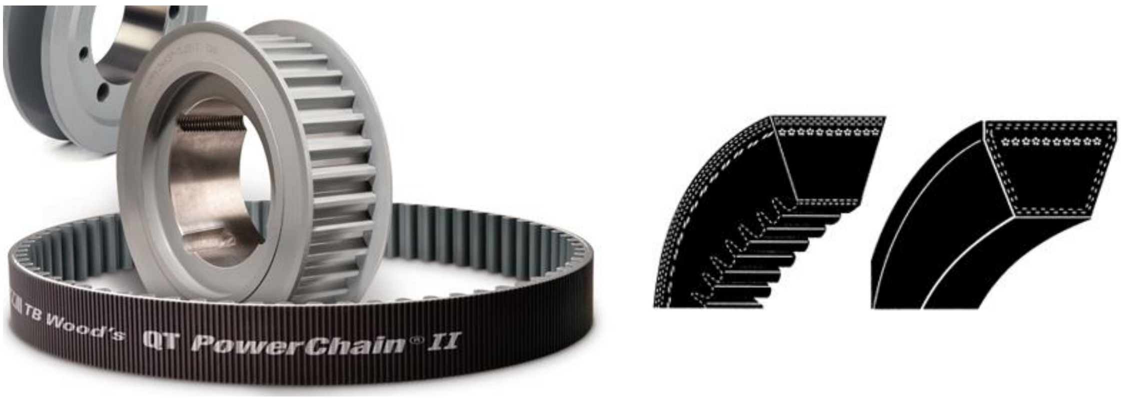
Belts

Most motors are connected to their loads through a transmission system, very frequently through a belt. About one third of the motor transmissions in industry uses belts. Belts allow flexibility in the positioning of the motor in relation to the load. Additionally, belts can also increase or decrease the speeds using pulleys of suitable diameters.

There are several types of belts namely: V-belts, cogged V-belts, synchronous belts and flat belts. While V-belts are the cheapest and are the most common type, other types can offer greater efficiency Table 1.

Table 1 Comparison of Belt Drive Characteristics [7]

	Typical Efficiency Range (%)	Suitable for Shock Loads	Periodic Mainte-nance Required	Change of Pulleys Required	Special Features
V-belts	90-98	Yes	Yes	No	Low first cost.
Cogged-V-belts	95-98	Yes	Yes	No	Easy to retrofit. Reduced slip.
Synchro-nous Belts	97-99	No	No	Yes, with higher cost	Low-medium speed applications. No slip. Noisy.



a) b)

Figure 28 a) Synchronous belt and sprocket; b) Cog belt (left) and V-belt

The V-belt losses are associated with flexing 4 times per cycle, slippage and a small percentage loss due to windage. With wear V-belts stretch and need retensioning. They also smooth with wear, becoming more vulnerable to slip. Thus V-belts need regular maintenance, which is a disadvantage in relation to other non-stretch type belts. Besides, their efficiency will drop if the load is above or below the full load (see Figure 29).

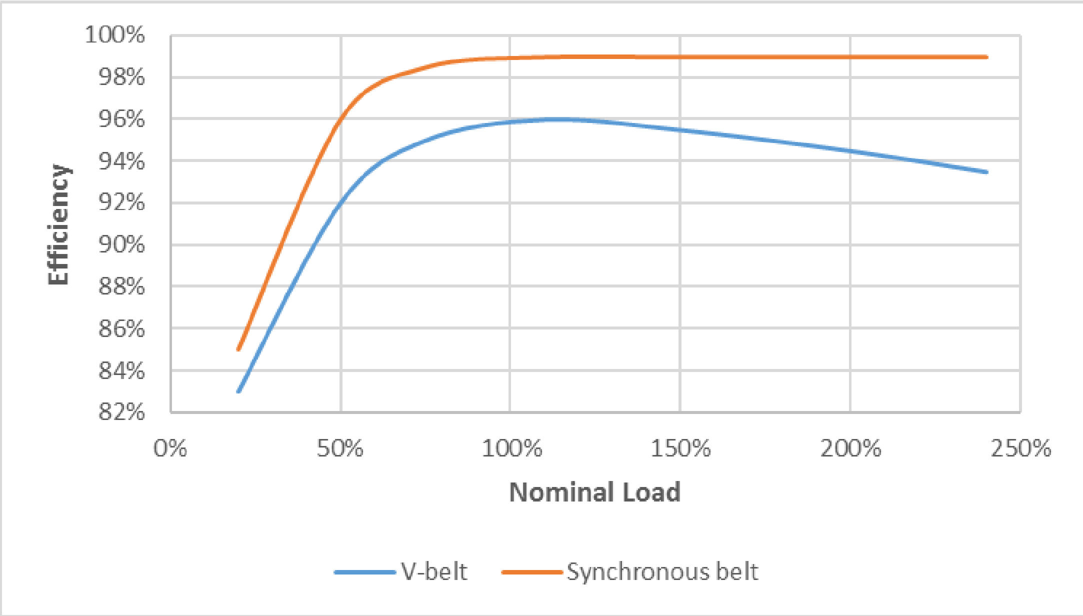


Figure 29 Efficiency Curve for a V-belt and a Synchronous belt [8]

The cogged V-belts have lower flexing losses, since less stress is required to bend the belt and so they are typically 1-4 percent more efficient than standard V-belts. They can be used on the same sheaves and pulleys as standard V-belts, last twice and require less frequent adjustments. The efficiency gained with cogged V-belts is larger when small pulleys are used. Cogged V-belts cost 20-30% more than standard V-belts, but their extra cost is recovered over a few thousand operating hours.

The most efficient belt is the synchronous design, with 97-99% efficiency, because it has low flexing losses and no slippage. Synchronous belts have no slippage because they have meshing teeth on the belt and pulleys. Unlike standard V-belts that rely on friction between the belt and the pulley grooves to transmit the torque, synchronous belts are designed for minimum friction between the belt and the pulley. Due to their positive drive, these belts can be used in applications requiring accurate speed control. Synchronous belts stretch very little because of their construction, do not require periodic retensioning and they typically last 4 times longer than standard V-belts. Retrofitting synchronous belts requires installing sprocket pulleys that cost several times the price of the belt. In cases where pulley replacement is not practical or cost effective, cogged V-belts should be considered.

Gears

The selection of efficient gear drives can be a potential for important energy savings. The ratings for gear drives depend on the gear ratio (the ratio of the input shaft speed to the speed of the output shaft) and on the torque required to drive the load.

Several types of gears can be used in motor transmissions, namely: helical, spur, bevel and worm. Helical and bevel gears are the most widely used and their efficiency can reach 98% per stage (each step of reduction or increase in the shaft speed). Spur gears are used for the same purpose as helical gears but are less efficient, so they should not be used in new applications. Worm gears allow a large reduction ratio (5:1-70:1) to be achieved in a single stage. Their efficiency ranges from 55% to 94% and drops quickly as the reduction ratio increases. Thus, worm gears should be whenever possible replaced with more efficient gears such as helical gears.

a)

b)

Figure 30 a) Worm gear; b) Helical gear

Chains

Unlike belts, chains typically have been used in low speed and high-torque applications. Like synchronous belts chains do not slip. A well-maintained chain may have an efficiency of about 98%, but wear can decrease this efficiency by a few points.

With the exception of silent chains, chains are noisy. Chains need readjustments and adequate lubrification, which may not be easy to provide. Thus the use of synchronous belts may seem as an attractive alternative to the use of chains.

Figure 31 Chain

3.5 Operation and Maintenance Practices

Regular maintenance (such as inspection, cleaning, lubrication, tool sharpening) is essential to maintain peak performance of the mechanical parts and to extend their operating lifetime [12]. This subject is dealt with in more detail in Chapter 8 – Energy and Maintenance.

Lubrification

A regular maintenance with the right frequency is necessary, to reduce to the minimum the friction of the bearings. Bearing friction wastes energy, increases the motor running temperature, decreases both the motor and lubrificant lifetimes. Both under or over lubrification can cause higher friction losses and shorten the bearings lifetime. Additionally, overgreasing can cause the accumulation of grease and dirt on the motor windings, leading to overheating and premature failure. The use of synthetic lubrificants can achieve substantial reduction in the friction losses.

Periodic Checks

The temperature, and the electrical and mechanical conditions of a motor should be checked periodically. Additionally, the mechanical efficiency of the end-use tool (pump, fan, weaving machine, etc.) directly affects the overall system efficiency. Monitoring wear and erosion in the end-use tool is especially important as its efficiency can be dramatically affected. For example, the erosion of the pump impeller will cause the pump efficiency to drop sharply.

In general facilities with good maintenance programmes will inspect the motor driven system every six months.

Cleaning and Ambient Conditions

Cleaning the motor casing, which is frequently required in some dusty industries, is also relevant because its operating temperature increases as dust and dirt accumulates on the case. The same can be said about providing a cool environment to the motor. The temperature increase leads to an increase of the windings resistivity and therefore to larger losses. An increase of 25 ^{o}K in the motor temperature increases the Joule losses by 10%.

Commissioning

The proper installation and start-up of the motor system is critical to ensure optimal efficiency and maximum lifetime. Particularly in large installations it is worth for a third party to thoroughly verify the whole motor systems and to check if the relevant specifications (electrical and mechanical) are met in a satisfactory way.

3.6 Load Management and Cycling

In addition to energy savings, demand reduction can also be achieved through the use of energy-efficient motor systems. Especially in the case of large investments, the economic benefits of demand reduction should also be taken into account when evaluating the cost-effectiveness of energy conservation investments. Additionally, motor cycling and scheduling can be performed, for load management purposes, to further reduce the power demand during peak periods. Typical loads which may benefit from cycling are loads with large time constants. Such loads include refrigeration equipment, air-conditioners, heat-pumps and other curtailable loads.

3.7 Benefits of Motor Systems Optimization

The optimization of motor systems within an organization provides multiple benefits which extend beyond the more direct energy and corresponding cost savings. Figure 32 shows some of these benefits.

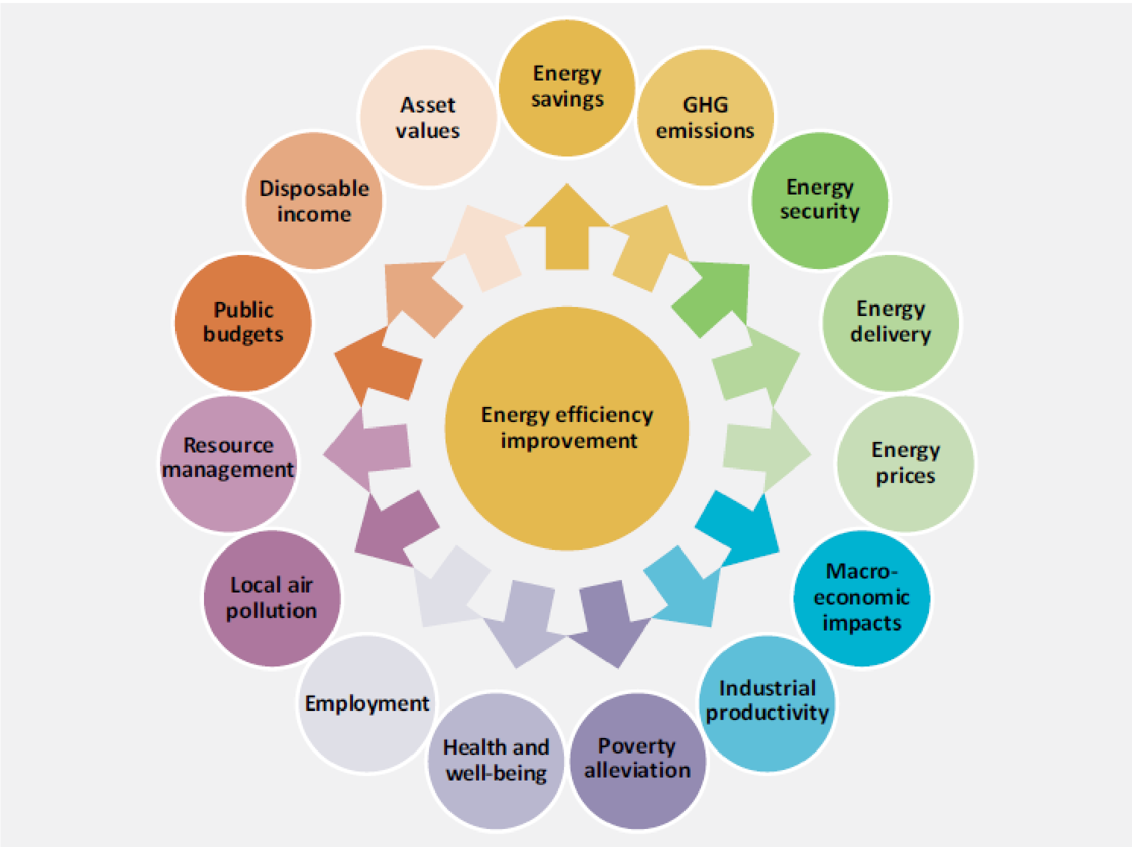


Figure 32 The multiple benefits of energy efficiency improvements [13]

The implementation of an effective motor system management program develops synergies between preventive and predictive maintenance programs, equipment operation and process productivity to establish a repair/replace policy based on a commitment to energy-efficient equipment selection and operation. Table 2 shows some of the benefits of implementing such a program.

Table 2 Benefits of Motor System Management programs

Increased Productivity	Improved Reliability	Reduced Costs
Greater control over process requirements	Scheduled downtime instead of breakdown maintenance	More efficient operation
Flexibility in meeting production requirements	Longer production runs between maintenance outages	Reduced maintenance costs
Reduced scrap and rework	Longer equipment life	Lower unit cost

4 Variable Speed Drives (VSDs)

A variable speed drive is an electronic system designed to control the speed of the motor's shaft by varying the frequency and voltage applied to the stator windings in order to meet the application speed and /or torque requirements.

VSDs have a wide variety of possible applications in electric drives. In the industrial sector it is possible to identify a few typical functions covering the majority of these motor applications, namely, robotics, machine-tools, materials handling, small and medium power process machines, compressors, centrifugal pumps and fans, etc.. In Table 3 the typical in power ranges of common applications can be seen.

Electrical VSDs, are normally incorporated into more or less complex systems. Depending on the driven machine, it is possible to:

- control speed (angular or linear), torque, position, acceleration or braking;
- optimise energy and/or material consumption, provided that a suitable sensor can be found and that the control algorithm can be defined;
- combine several machines and control their speeds in a coordinated manner;
- communicate with different systems or different hierarchy levels in the same system, the drive and the machine being considered as a single unit within a structure grouping together the complete process.

Table 3 Positioning in power of the typical industrial applications

Application	P<10 kW	10<P<50 kW	50<P<500 kW	P>500 kW
Robotics	■			
Machine Tools	■	■		
Material Handling	■	■		
Small and medium process machines		■	■	
Large machines (e.g. mills, compressors)				■
Centrifugal machines (excluding large machines)	■	■	■	
Replacement of thermal engines				■

The possibilities offered by VSDs are enhanced by the integration with computerised manufacturing systems.

The speed of the rotating field created by the induction motor stator windings is directly linked with the voltage frequency applied to the windings. Electronic Variable Speed Drives can produce variable frequency, variable voltage waveforms. If these waveforms are applied to the stator windings there will be a shift of torque-speed curve, maintaining a constant pull-out torque, and the same slope of the linear operation region of the curve. In this way, the motor speed is going to be proportional to the applied frequency generated by the VSD (Figure 33).

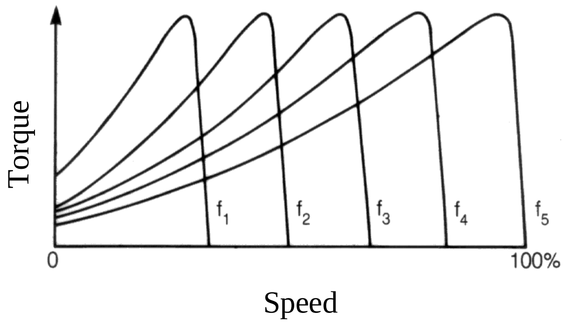


Figure 33 Speed-Torque Curves for an Induction Motor ($f_1<f_2<f_3<f_4<f_5$ and f_5=50Hz).

Figure 34 shows the general configuration of most VSDs. The three-phase, 50Hz alternated current (AC) supply is initially converted to direct current (DC), then filtered and finally, the DC/AC inverter converts the DC voltage to the variable voltage and variable frequency output applied to the motor.

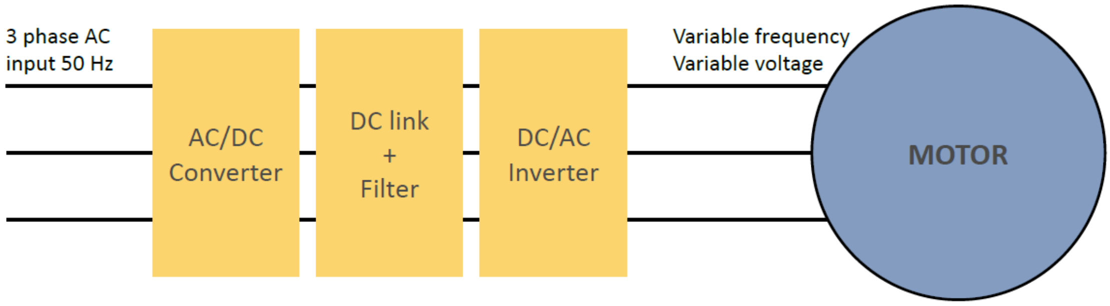


Figure 34 General Configuration of Inverter Based VSDs.

The adjustment of the motor speed through the use of VSDs can lead to better process control, less wear in the mechanical equipment, less acoustical noise, and significant energy savings. However, VSDs can have some disadvantages such as electromagnetic interference (EMI) generation, current harmonics introduction into the supply and the possible reduction of efficiency and lifetime of old motors.

Table 4 presents an overview of controlled AC-drive technologies, showing five basic forms of power electronic VSDs.

Table 4 Overview of power electronic VSDs

Type of VSD	Main characteristics	
	Advantages	***Disadvantages***
Pulse-Width Modulation (PWM) Voltage Source Inverter (VSI)	Good power factor throughout speed range. Low distortion of motor current. Wide speed range (100:1). Multi motor capability.	Limited to VSDs bellow 1 MW. Slightly (about 1%) less efficient than VSI or CSI. Basic circuit has no regeneration capability.
Six-step Voltage-Source Inverter (VSI)	Good efficiency. Simple circuit configuration. Wide speed range (10-200%). Multi-motor capability.	Poor power factor at low speeds (unless a rectifier/chopper AC/DC converter is used). No regeneration capability. Operation below 10% of rated speed can produce cogging.
Force Commutated Current-Source Inverter (CSI)	Simple and robust circuit design. Regenerative capability. Built-in short circuit protection. Wide speed range (10-150%).	Bulky. Poor power factor at low speed/load. Possible cogging below 10% of rated speed.
Load-Commutated Inverter (LCI)	Simple and inexpensive circuit design. Regeneration capability. Built-in short-circuit protection.	Poor power factor at low speed. Can only be used with synchronous motors.
Cyclo-Converters	Can operate down to zero speed. High torque capability with field-oriented control. Can be used with induction and synchronous motors.	Cannot be used above 33% of input frequency. Complex circuit design. Poor power factor at low speed. Drives above 1 MW

The criteria for VSD selection involve knowing of a certain amount of basic data which namely includes: power required, supply voltage, torque/speed requirements, speed range and speed accuracy. A VSD must be capable of:

- Starting the controlled load;
- Driving this load in accordance with the operating requirements;
- Stopping this load in accordance with the criteria linked to the operating mode.

To meet these three functions, common to all applications, it may be necessary to add the positioning or the synchronisation with other devices in the system.

To ***start*** a load the electromagnetic torque of the motor must be larger than the total resistive torque. The difference gives the acceleration torque, which is a function of the total inertia of the system and of the required accelerating time. Table 5 shows a few examples of starting requirements linked to typical applications and gives possible solutions.

Productivity normally increases with speed. The quality increases with steady-state accuracy if the load varies little during the production cycle. Dynamic accuracy is relevant if the load cycle significantly varies and if there are many variations in the torque reference. Often, the transmission quality of the shaft line (backlash, elasticity, flexion, torsion, etc.) limits the improvement in performance due to the use of VSDs. One of the characteristics of VSDs is that the drive can be located as close as possible to its utilisation. It is therefore possible to reduce to a minimum the problems linked to couplings and transmissions (backlash, elasticity, critical speeds).

In applications that require a wide range of speeds and/or accurate speed control, the most appropriate technique is to use electronic variable speed drives (VSDs) [14]. VSDs can match the motor speed to the load requirements. Motor-driven loads can be classified into four main groups according to whether the torque required increases quadratically or linearly, remains constant, or decreases as the speed increases (Figure 35). The mechanical power is equal to the product of torque times angular speed. In centrifugal pumps and fans (quadratic torque loads) the power required varies approximately with the cube of the motor speed. This means that in a fan system, only about half of the full power is required to move 80% of the rated flow.

Table 5 Examples of starting requirements linked to certain typical applications and possible solutions.

STARTING		
Requirements	***Typical applications***	***Possible solutions***
Limiting mechanical shocks	Belt conveyor, escalator, conveyor for fragile products	Speed ramp
Eliminating backlash	Gearings, transmission handling line	Parabolic or S-shaped ramp
High inertia machine	Centrifuge	Motor with high starting torque
Machine with high resistive torque	Crusher, Grinder	
Load with driving torque	Lift	System operating in 2 or 4 quadrants
Frequent starting in a given time	Handling machine	Appropriate thermal rating
Within a time limit	Centrifuge smoke extractor	Speed ramp
Within a time and space limit	Ski lift	Special acceleration control

In terms of response, the pumps and fans controlled by VSDs can respond to changing conditions faster and more reliably than valves or dampers can. This is particularly true at the extremes of the flow range where valves become highly nonlinear, even when equipped with linearizing trims.

In the case of cube-law loads (ex.: centrifugal fans, pumps and compressors), significant reductions in the consumption can be obtained, compared to the throttling flow control. VSDs can also make induction motors run faster than their normal full speed ranges, provided that the rotors can withstand higher operating speeds. Therefore, VSDs have also the potential to extend the useful operating range of compressors, pumps, and fans. For the many applications (such as forced draft fans) that are limited by fan or pump capability, a properly selected VSD and motor can extend both the high and the low end capability.

VSDs also isolate motors from the line, which can reduce motor stress and inefficiency caused by varying line voltage, phase unbalance, and poor input voltage waveforms. In some applications VSDs can drive multiple motors simultaneously, as in many web processes. For example, a single 100 kW PWM-VSD could be used to drive two 50 kW induction motors at exactly the same frequency. This approach can provide significant cost savings.

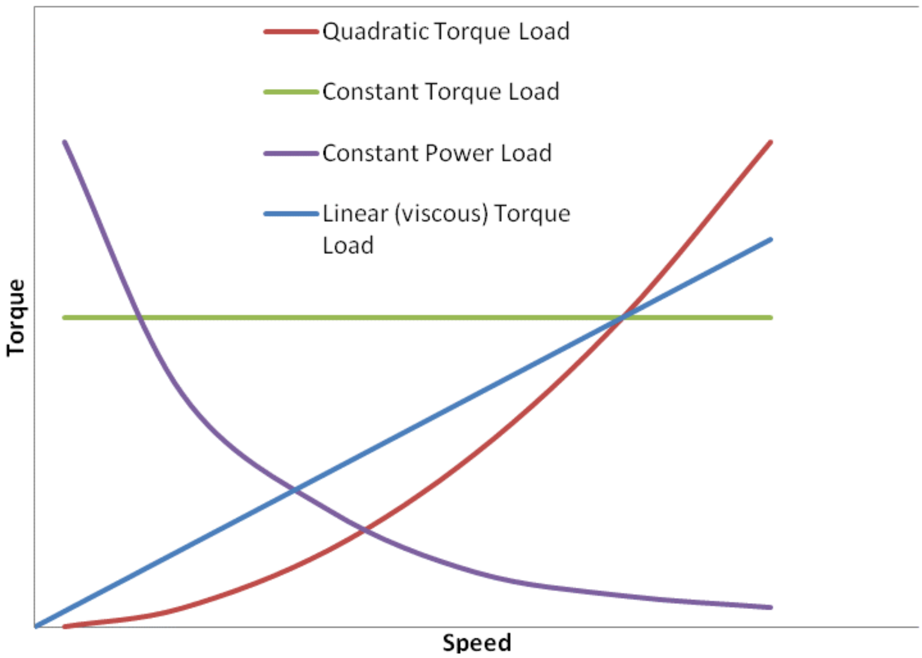


Figure 35 Types of torque-speed curves:

-Quadratic torque load (e.g. centrifugal fans, blowers, pumps and compressors);
-Constant torque load (e.g. conveyors, positive displacement pumps, screw compressors, reciprocating compressors, crushers);
-Constant horsepower load (e.g. traction, winders, rolling mils);
-Linear Torque Load (e.g. Calenders with viscous friction coupling, mixers, eddy current brakes)

Stopping a system can be carried out in different ways depending on the performance required by the application. Table 6 summarises the main aspects related to the stopping operation. The problem of stopping is linked to that of positioning.

Table 6 Main aspects related to the VSD stopping operation.

STOPPING		
Requirement	***Typical applications***	***Possible solutions***
Simple stopping	Fans	Freewheel or mechanical brake
Limit mechanical shocks	Belt conveyor drives	Deceleration ramp, torque limitation
Backlash elimination	System incorporating gears	Parabolic deceleration ramp
Short time	Emergency stop centrifuges	Speed ramp, DC injection
Load with driving torque	Lifts, hoists	Reversing drive
Electrical braking without motor heating, with or without regeneration	Rolling mills, electric traction	Resistive dissipation or regenerative braking

In summary, advantages of VSDs are:

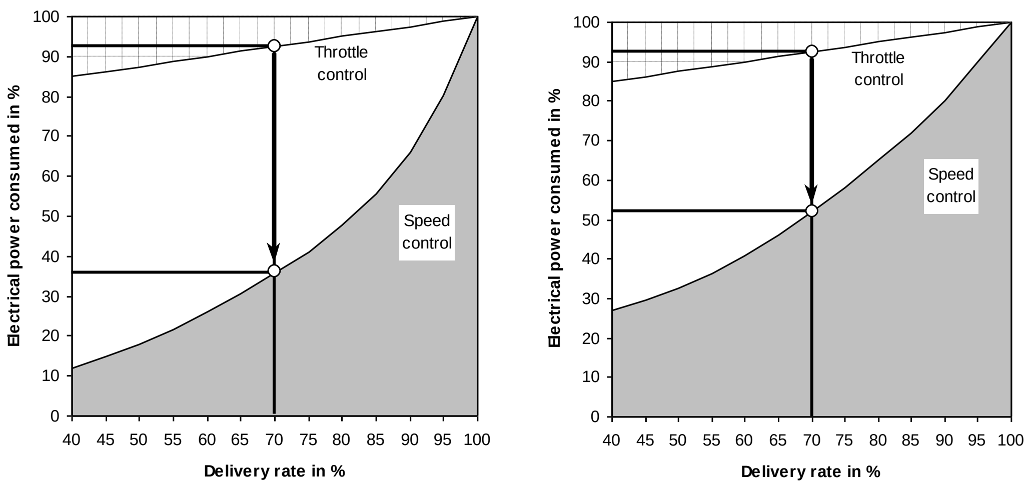
- Energy savings associated to the speed control;
- Improvement of the dynamic performance of induction motors;
- High efficiency of the VSDs (96-98%) and high reliability;
- High power factor (if active front end is used);
- Small size and location flexibility;
- Soft starting (savings!) And controlled/regenerative braking;
- Motor protection features;
- Lower acoustic noise and improvement of the process control;
- Less wear maintenance needs of the mechanical components.

There are also a few possible disadvantages to the use of VSDs, which can be mitigated is certain precautions are taken, such as:

- Inject harmonic distortion in the network
- Voltage spikes leading to failure of insulation in windings of old motors
- Bearing current leading to premature failure

4.1 Pumps

Single pump - The centrifugal pumps without lift (e.g. closed loop circuit), respect the cube power law, i.e., the consumed power is proportional to the cube of the speed, as shown in Figure 36 (a). If the user wants to reduce the flow in the process, valve control can be used, or alternatively speed control can be applied, using a VSD. Although both techniques fulfil the desired objective, the consumed energy is significantly higher when valve throttle control is used. If there is a system head associated with providing a lift to the fluid in the pumping system the pumps must overcome the corresponding static pressure, as shown in Figure 36 (b).



(a) (b)

Figure 36 Electrical power input of a pump with throttle control vs. one with speed control: (a) without static pressure head (e.g. recirculation systems); (b) with static pressure head.

In these pumping systems the mechanical energy is used to overcome the friction in the pipes, plus the mechanical work associated with lifting the fluid against the gravity as shown in Figure 37.

If the percentage of the power associated with overcoming the pipe friction is relevant, energy savings can still be achieved although typically less than in systems without static pressure head.

The overall efficiency of the pumping system depends on the efficiency of the different components of the system. Figure 38 shows an example of the power absorbed by a pump system with different components. For the same end-use power, the inefficient system absorbs more than twice the power absorbed by the optimized system.

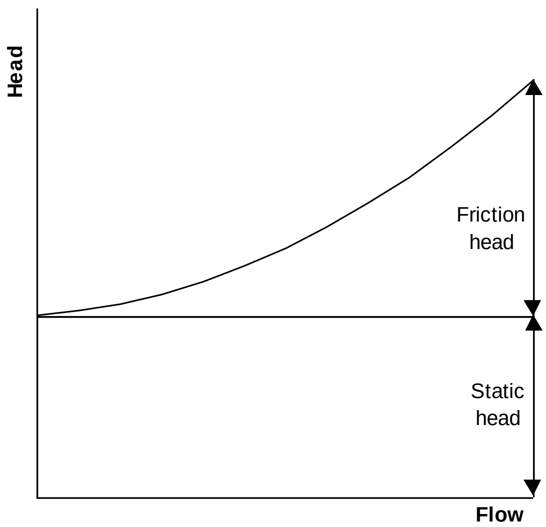


Figure 37 Total system resistance from frictional losses plus static head losses.

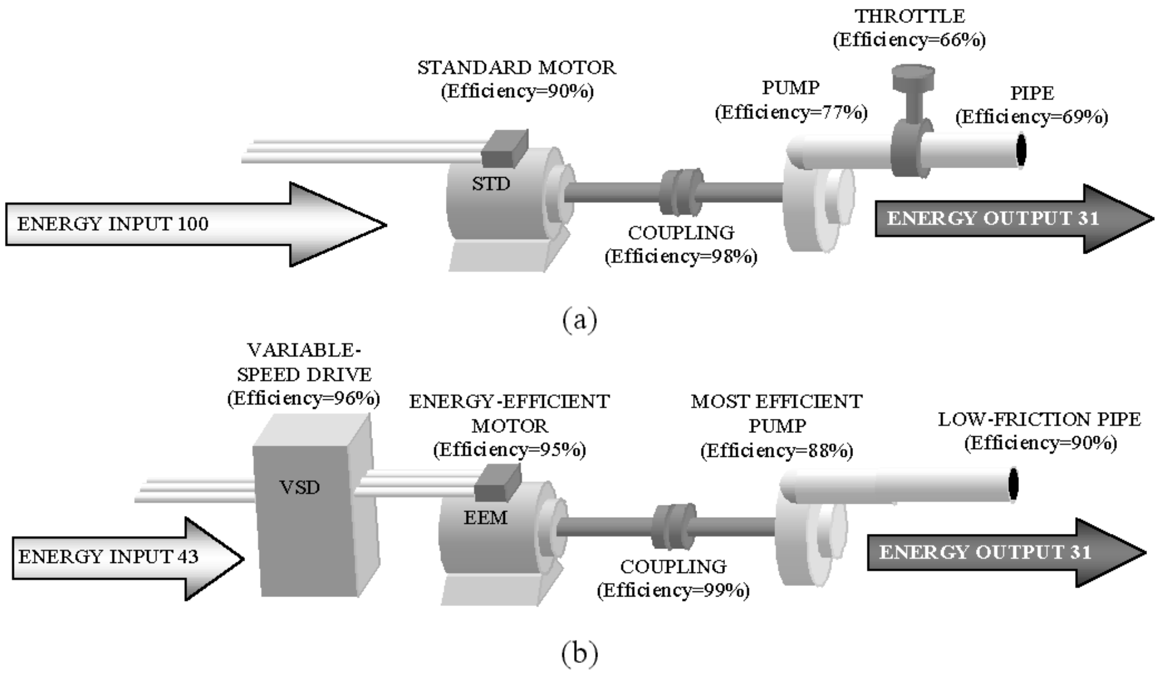


Figure 38 Two pumping systems with same output: (a) Conventional system (Total Efficiency = 31%); (b) Energy-efficient pumping system combining efficient technologies (Total Efficiency = 72%). [15]

Staged pumping plant - In many pumping applications several pumps are used in parallel to produce the required flow. Operating all pumps at reduced speed rather than cycling the pumps on/off according to the demand, significant energy savings can be reached. For example, in a low static head two pump system, with independent piping circuits, operating both pumps at 50% of the rated flow requires approximately 25% of the power required for a single pump operating at 100%. Other advantages are that pumps stay warm (no condensation in the windings), seals stay wet and alive, also eliminating high-shock starts on system. Figure 39 illustrates this situation. Also it is possible to control the "water-hammer" effect which degrades the pipes by controlled acceleration/deceleration using VSDs.

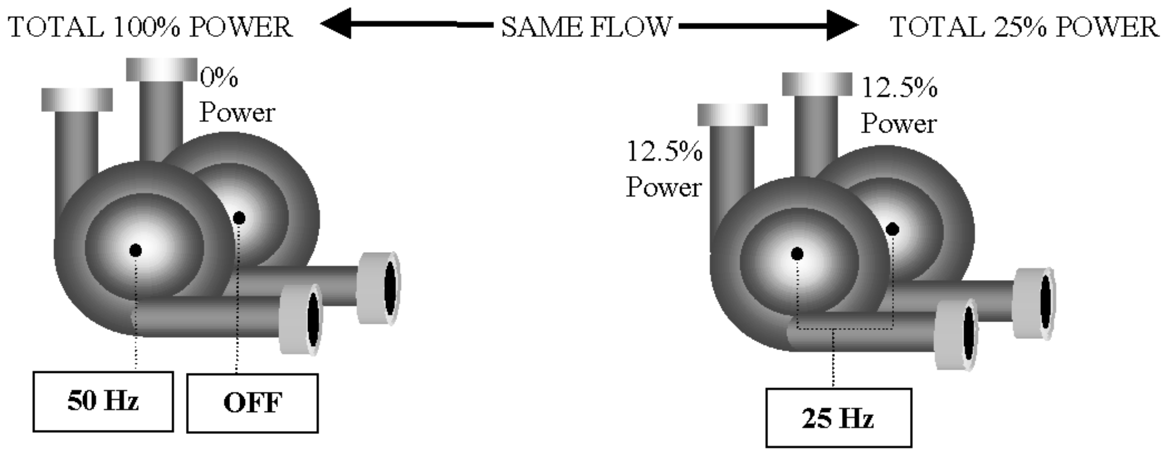


Figure 39 Pumping plant: Useful relationship to consider with two independent closed loop circulating systems where "head" is not a major factor.

4.2 Fans

Savings from adding variable speed control to fans can be significant even with fairly heavily loaded motors. Figure 40 illustrates the savings potential with an VSD versus common throttling methods.

High amounts of energy are wasted by throttling the air flow versus using adjustable speed. The worst method is outlet dampers, followed by inlet vane control. For 50 % flow, a VSD can save 80% and 68% of the consumed power when compared with dampers and inlet vanes, respectively. For example, a 100 kW motor driving a load continuously throttled to 50 percent of output will save almost 18000 Euro per year (assuming 0.06 Euro/kWh, 6000 hours per year). The energy consumption in these loads is so sensitive to speed that the user can achieve significant savings with even modest speed adjustments.

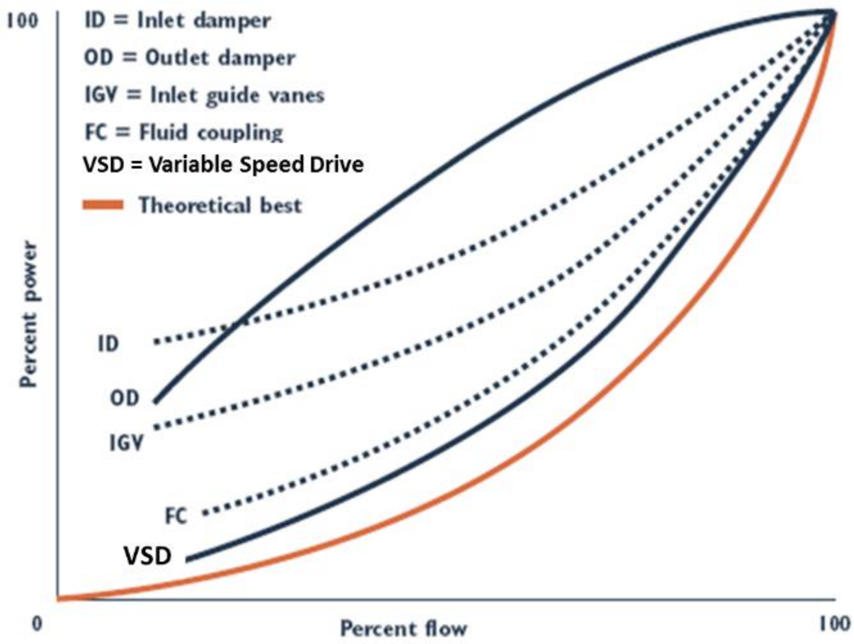


Figure 40 Relative power consumption of different air flow control methods.

Example: In the heat exchanging systems, such as that represented in Figure 41 and Figure 42, the pumps speed may be controlled as a function of the process or zone temperature, and the fans speed as a function of the coolant water/fluid temperature, by means of VSDs or using two-speed SCIMs. The "heat exchange" capacity can also be adjusted by energizing/de-energizing each of the four subsystems. The combined pump and fan speed control as a function of the temperature (Figure 41), compared with ON/OFF cycling control, leads to a more stable temperature in the controlled zone/process and to a more efficient operation, typically decreasing the fan energy consumption in the range of 25-50%. Such systems can be found, for example, in cooling towers and roof top chillers.

In the system represented in Figure 42, if the cooling water circuit is closed and only 50% of the heat dissipation is needed, it is relevant to optimize the reduction of the speed of the fans and of the pumps, providing that in the end the overall thermal resistance between the process to be cooled and the environment is kept at 50%, in order to maintain a constant temperature for half of heat loss production. The fan and pump speed decrease will lead to cubic reduction in the required power.

If the amount of heat to be extracted from the process cooling system represented in Figure 42 is reduced to 75%, 50% or 25%, assuming independent closed-circulation piping systems, the user may switch off 1, 2 or 3 heat exchangers (pumps and fans), leading to a reduction of 25%, 50% and 75% of the required hydraulic/pneumatic power, respectively, or, alternatively, reduce the speed of the pump and fan in the 4 heat exchangers to 75%, 50% or 25%, by means of VSDs, leading to a reduction of 57.8%, 87.5% and 98.4% of the required hydraulic/pneumatic power, respectively [8].

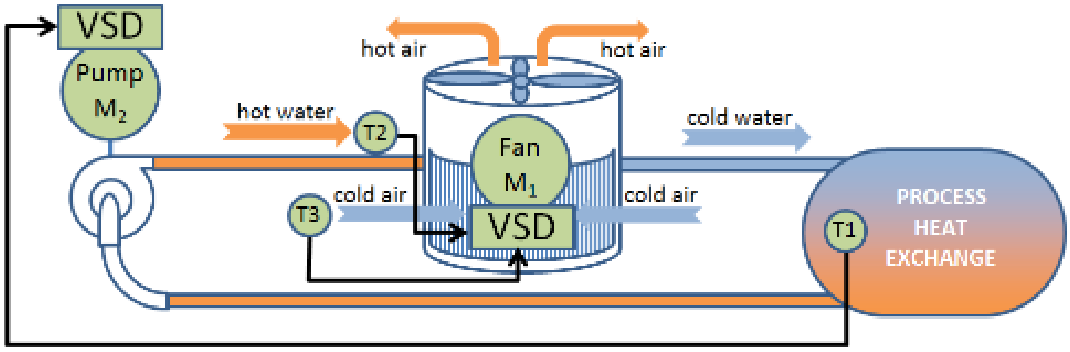


Figure 41 Simultaneous closed-loop speed control of the pump and fan of a heat exchanger or chiller [16].

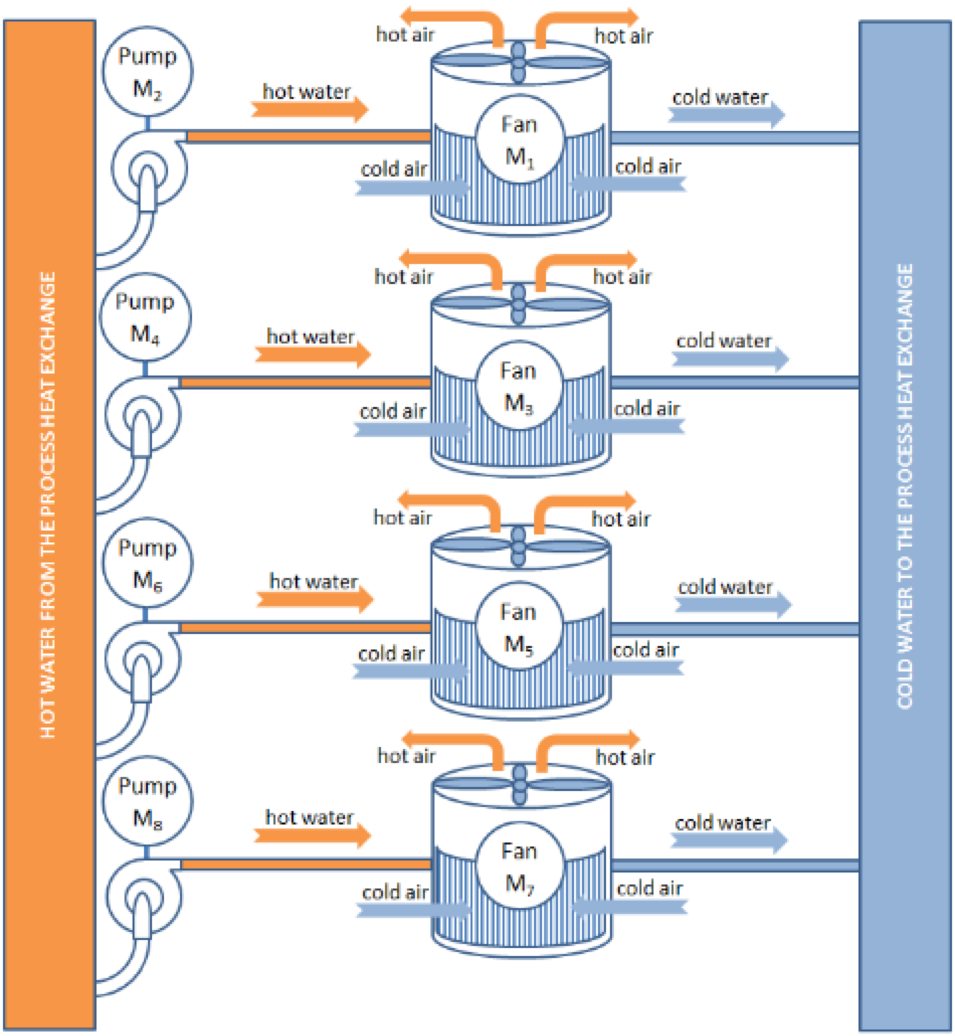


Figure 42 System with four heat exchangers [16]

4.3 Compressors

Rotary screw and piston air compressors are essentially constant torque loads and can also benefit from the application of variable speed control. The savings related to the use of variable speed control are dependent on the control system that is being replaced. In Figure 43 the energy savings achieved by fitting a VSD to a rotary screw compressed air unit, compared to other methods of flow control at partial load, can be seen. In a compressor, with modulating control, if the demand is 50% of rated capacity, the energy savings associated with the VSD integration is about 38%.

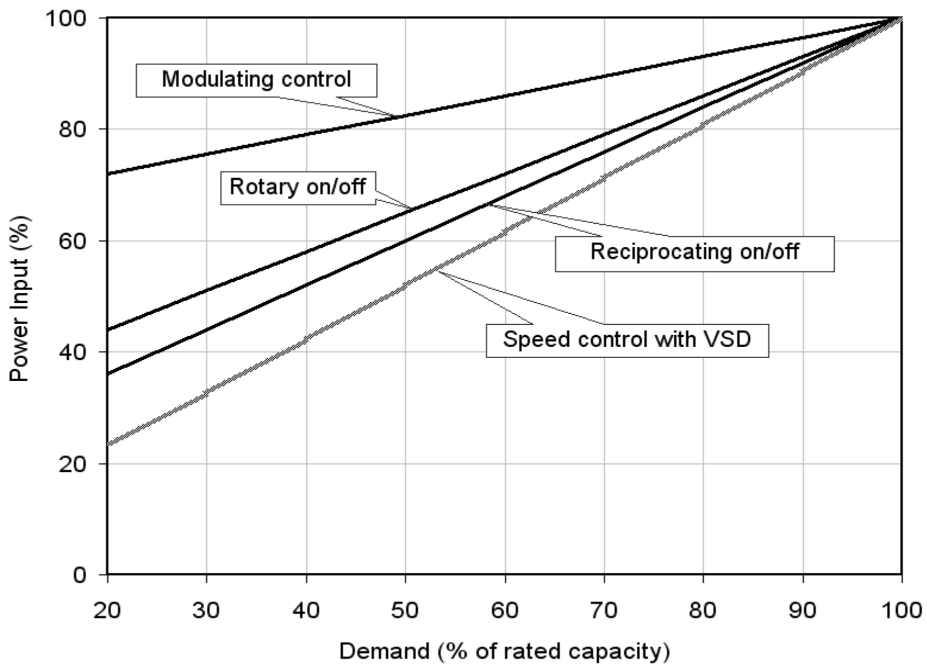


Figure 43 ***Energy saved by using a VSD on a rotary srew air compressor.***

Energy savings with constant torque loads is typically considerably less than with centrifugal pumps or fans which obey the power cube law, and so to retrofit a VSD to a compressor it is less likely to be economic on the grounds of energy savings alone. Additionally, care needs to be taken to ensure adequate lubrication at reduced speeds. However, the introduction of screw compressors with integral speed control has enabled the additional price of variable speed control to be significantly reduced. These machines therefore deserve to be considered for all new applications with long running hours, when there is a widely varying demand. Further energy savings will also be achieved through improved pressure control, by reducing the mean generation pressure.

Another example of VSD application in compressors is for refrigeration purposes (Figure 44). The use of VSD for temperature control (floating head operation) in the refrigeration pumps/compressors (ex.: Walk-in Freezer) can eliminate the on/off cycling, with large energy savings. The temperature control can also be improved, in terms of differential between internal and external temperatures.

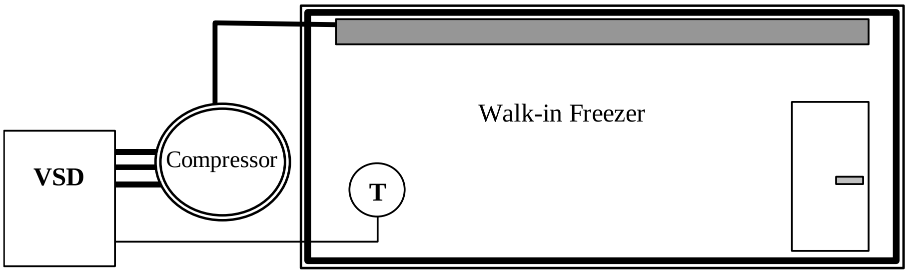


Figure 44 Variable speed refrigeration compressor.

4.4 Lifts

New VSD topologies allow the braking energy to be injected back to the source/grid. This feature can be a way of saving a significant amount of energy in applications with frequent braking operations, namely, lifts. This is only possible if the motor mechanical transmission allows this mode of operation. When the lift is going down, and the load weight (people inside) is larger than the counterweight, then the motor torque is in opposite direction to the speed, i.e., the motor is braking. In the same way, when the lift is going up unloaded, energy savings can be reached if the motor is controlled with a regenerative VSD.

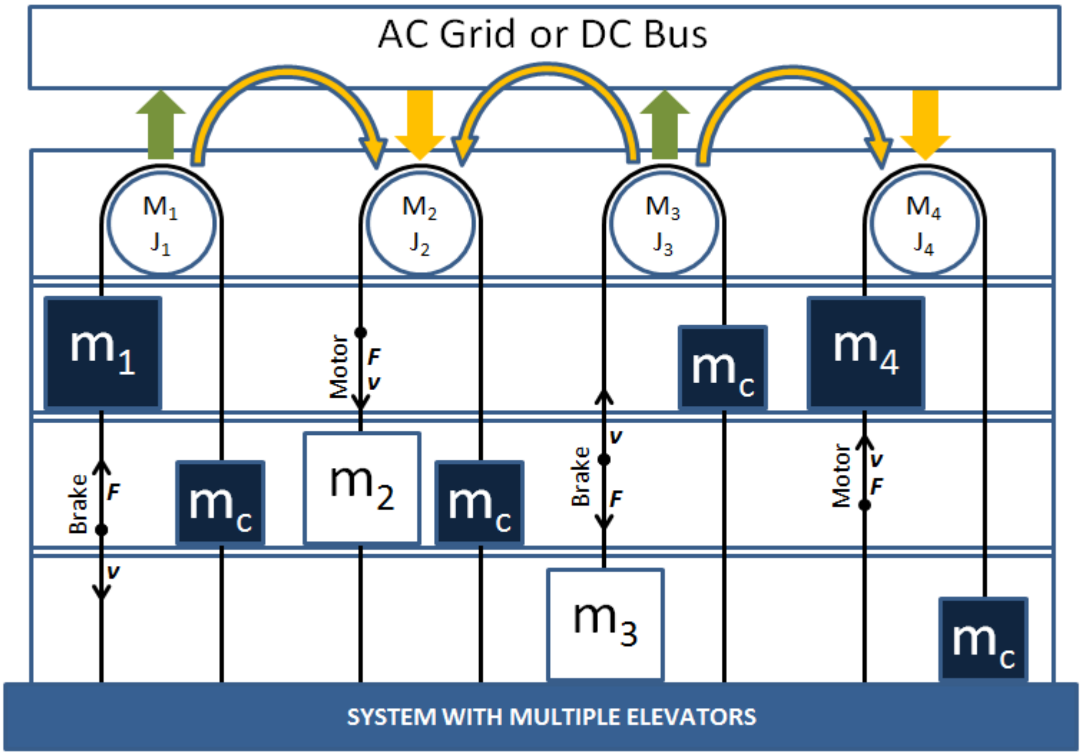


Figure 45 Lift motor operating modes (f_M - Driving force ; v - Speed).

In Figure 45, possible energy savings in lifts, using different technologies, can be seen. The use of regenerative VSD system, and special gear, the consumed energy can be reduced to 19%, when compared to a conventional system, using a pole changing drive. Permanent magnet motors with direct drive (without gears) coupling and regenerative braking are also being introduced in new high efficiency lifts.

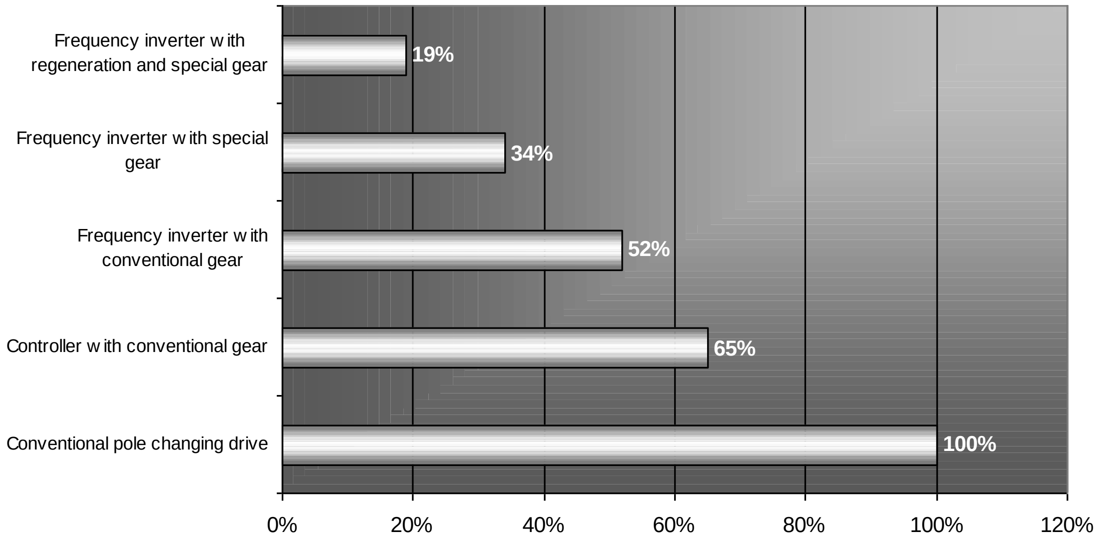


Figure 46 Energy balance of lifts, Average energy consumption, percentage, Source: Flender-ATB-Loher, Systemtechnik.

4.5 Centrifugal Machines and Machine-Tools

In high inertia loads (e.g. machine-tools) or/and high speed loads (e.g. centrifugal machines), with frequent accelerating/braking operation, it is possible to save significant amounts of energy. When running, this type of loads has a large amount of kinetic energy that, in a braking process, can be regenerated back to the grid, if a regenerating VSD is used (same regenerative process as used in lifts). Examples of this type of loads are high speed lathes with an automatic feeder or high inertia saws (Figure 47).

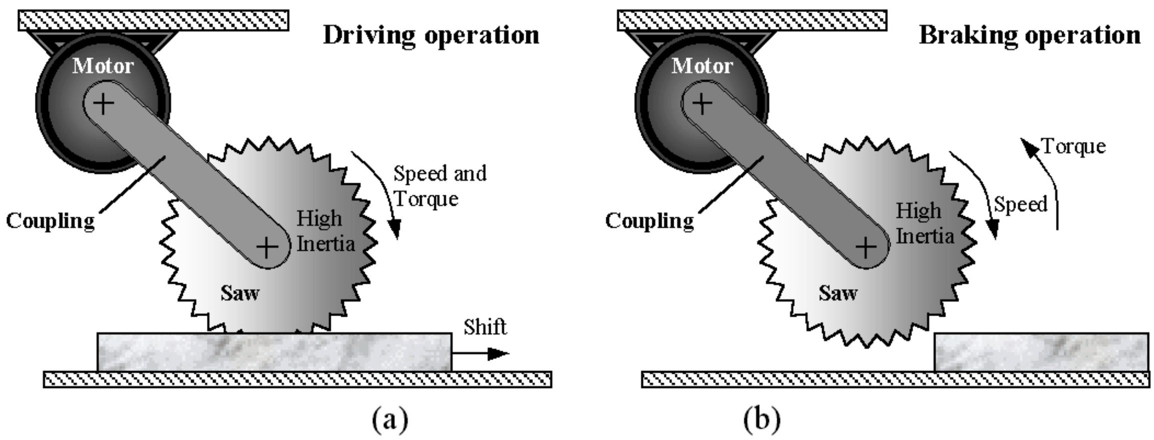


Figure 47 Operation modes of a high inertia saw: (a)Driving operation; (b)Braking Operation.

In fact, when a high inertia saw or high speed lathe is running the speed and torque are in the same direction, but when the operation ends, typically it is necessary a fast stop. So, the braking energy can be re-injected to the grid, instead of been dissipated in a resistance. Another important aspect is the acceleration process. As it can be seen in Figure 48, if the motor is simply turned on (situation (a)), without any speed control, the rotor losses will be higher than if is used a pole changeable motor (situation (b)). A more efficient acceleration technique uses a VSD (situation (c)), that will significantly reduce the energy consumption, comparatively to the other mentioned techniques.

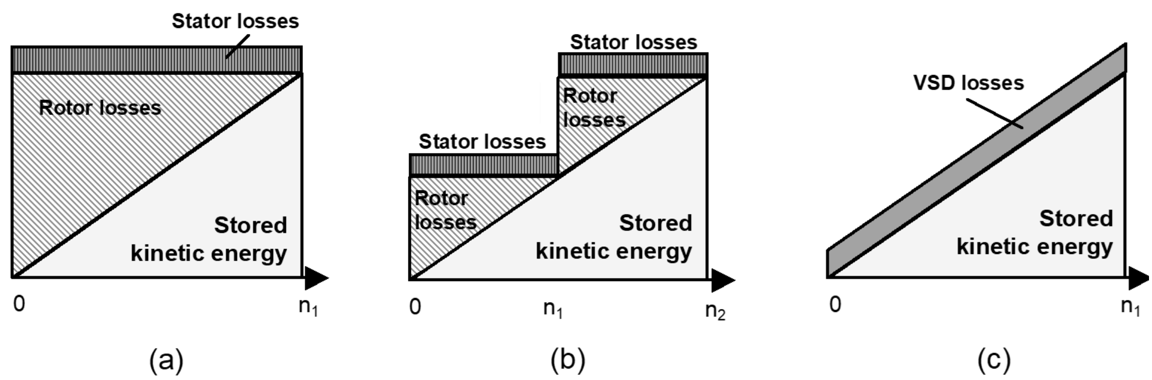


Figure 48 Energy-Consumption for an Acceleration Period: (a) Standard Motor; (b) Pole Changeable Motor; (c) Variable Speed Drive (VSD) [source: Siemens].

4.6 Conveyors

In the constant torque devices (ex.: horizontal conveyors), the torque is approximately independent of the transported load (is only friction dependent). Typically, the materials handling output of a conveyor is controlled through the regulation of input quantity, and the torque and speed are roughly constant. But, if the materials input to the conveyor can be changed, it is possible to reduce the speed (the torque is the same), and, as it can be seen in Figure 50, significant energy savings will reached, proportional to the speed reduction.

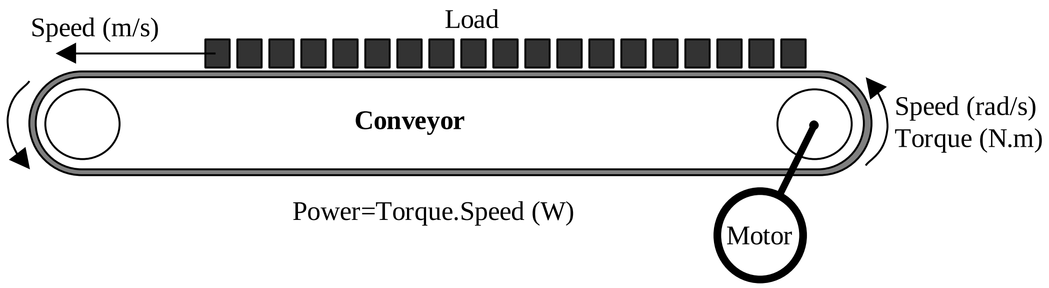


Figure 49 Power required by a conveyor.

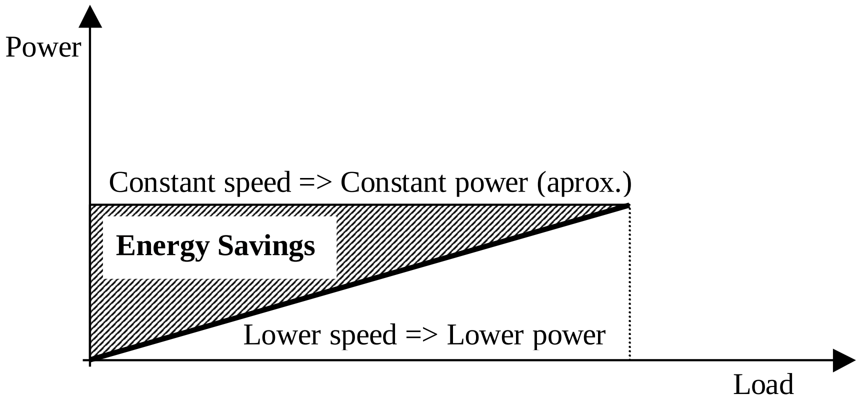


Figure 50 Energy savings in a conveyor using speed control, in relation to the typical constant speed.

5 Energy Efficiency Standards

Almost all the major economies have some kind of voluntary or mandatory regulatory scheme regarding motor efficiency. Most of these economies have mandatory minimum efficiency levels for motors sold in the respective countries and labelling schemes for the promotion of higher efficiency motors.

Several different energy efficiency levels/classes were, until recently, in use around the world, increasing potential confusion and creating market barriers.

CEMEP-EU	EFF1/EFF2/EFF3
USA	EPAct/NEMA Premium
Australia	Minimum Efficiency/High Efficiency
China	Grade 1, 2 and 3

To further increase confusion, these classifications schemes relied on different test methods which can produce significantly different results. Therefore, efficiency levels were not straightforwardly comparable.

Furthermore, the measurement tolerances varied in the different test methods, and the impact of the supply frequency (50 Hz or 60 Hz) used during the test on the final test results complicated things further.

With the purpose of harmonising the different energy efficiency classification schemes for induction motors in use around the world, the International Electrotechnical Commission (IEC) introduced, in 2008, a new classification standard – IEC60034-30 [17]. The standard covered single-speed three-phase 50 Hz or 60 Hz cage induction motors with a rated output PN between 0,75 kW and 375 kW.

IEC 60034-30 has recently been revised. It is now divided into two parts:

- Part 1 - Efficiency classes of line operated AC motors (IE code)
- Part 2 - Efficiency classes of variable speed AC motors (IE code)

IEC 60034-30-1:2014 [18] significantly broadens the scope of products covered. The power range has been expanded to cover motors from 120 W to 1000 kW. All technical constructions of electric motors are covered as long as they are rated for direct on-line operation. These include single-phase motors, not just three-phase motors as in the previous edition, and line-start permanent magnet motors.

In this updated standard the IE4 class (Super-Premium), which in the previous standard was only envisaged, is now defined. Furthermore, a new superior IE5 class is introduced although not yet fully defined. It is the goal to reduce the losses of IE5 by some 20 % relative to IE4.

The levels of energy efficiency defined are:

- IE5 – Ultra Premium efficiency (Preliminary values –Still under development)
- IE4 – Super Premium efficiency
- IE3 – Premium efficiency (equivalent to NEMA Premium)
- IE2 – High efficiency (equivalent to EPAct, and to old EFF1)
- IE1 – Standard efficiency (equivalent to old EFF2)

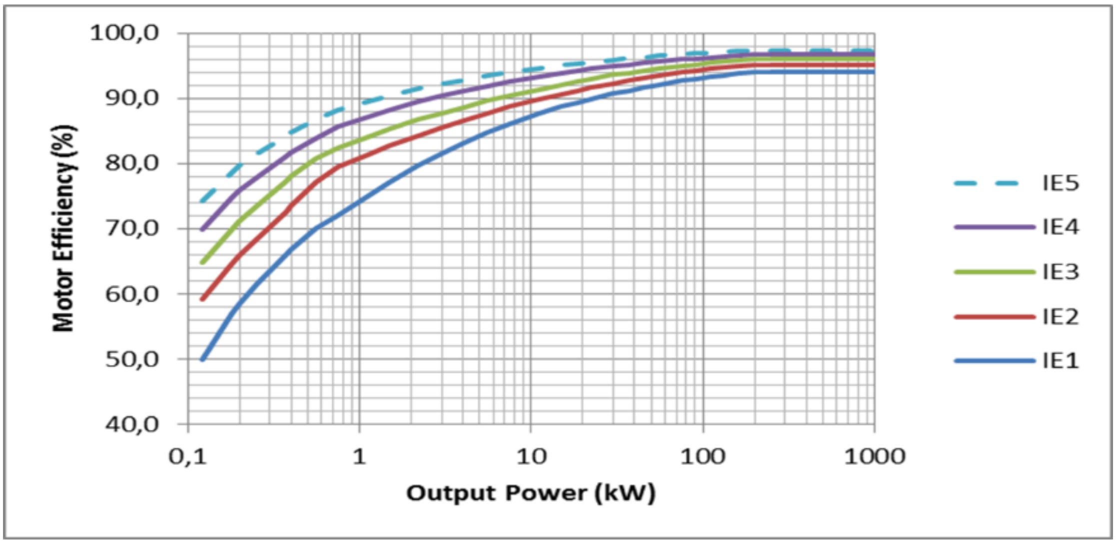


Figure 51. Efficiency levels in the IEC 60034-30-1 (2014) classification standard for 4 poled motors

For the purpose of efficiency classification according to standard IEC 60034-30-1, the preferred test method as indicated in standard IEC 60034-2-1 (2014) [19] for testing must be used. This means that in practice the "Summation of losses, with and without load test, P_{LL} determined from residual losses" is used for all 3 phase motors in the 0.75 – 375kW power range.

Both standards have contributed to end the difficulties manufacturers encounter when producing motors for a global market and will help make it a more transparent one.

At the time of the first edition of IEC 60034-30, in 2008, the efficiency levels of the Super Premium (IE4) class were believed to be too high to be achieved with standard induction motor technology, particularly for small motors. However, it was expected that advanced technologies (e.g. Permanent Magnet motors, Synchronous Reluctance motors) would enable manufacturers to design motors to achieve this efficiency class with mechanical dimensions compatible to existing motors of lower efficiency classes, making this motors commodity products. Today, induction motors have reached the market with IE4 efficiency levels and the use of different advanced technologies can produce motors with efficiencies above the IE5 efficiency threshold, as can be seen in Figure 52.

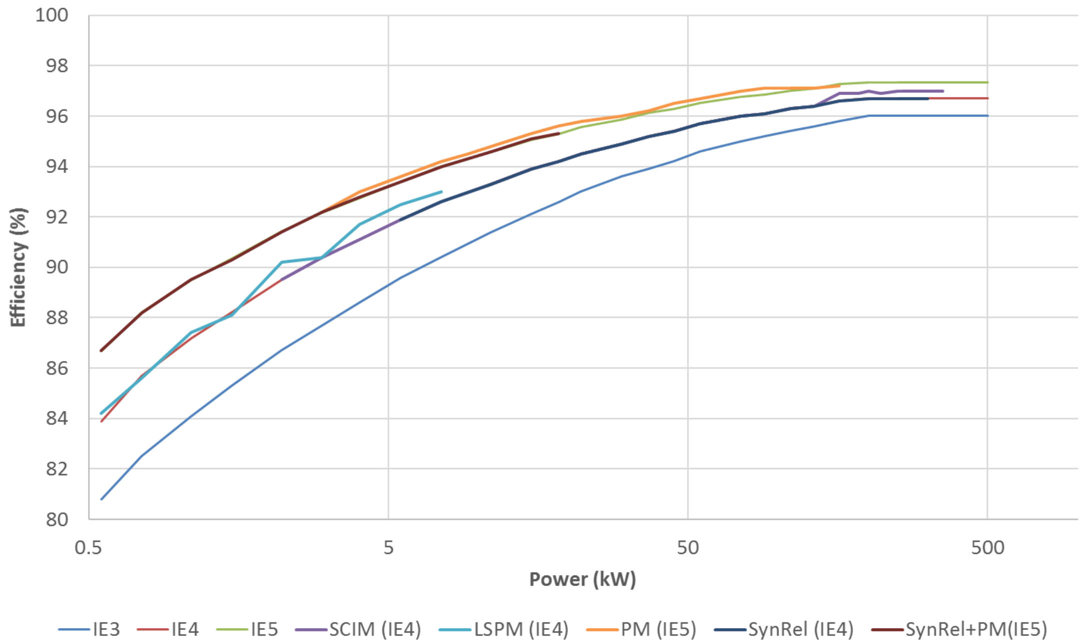


Figure 52. Overview on the motor efficiency classes defined in the IEC600-34-30-1 standard and on the commercially available motor efficiency (catalogue data)

Most induction motors sold before 2000 some of which are still being used today have poor efficiencies (below IE1). In most cases the low efficiency is aggravated by poor maintenance and repair practices.

New motor applications are increasingly being installed with VSDs, enabling speed and torque control. Motors equipped with VSD are expected to reach over 50% of all sold motors leading to significant energy savings for applications that benefit from partial speed operation.

This increasing market importance of motors driven by VSDs has led to the development and publication of efficiency testing and classification standards for motors operating on a non-sinusoidal supply, which leads to increased losses in the motor due to the non-sinusoidal supply (additional harmonic losses):

- IEC 60034-2-3:2020, REF Specific test methods for determining losses and efficiency of converter-fed AC motors [20].
- IEC/TS 60034-30-2:2016, Efficiency classes of variable speed AC motors (IE-code) [21].

The technical specification[2] IEC TS 60034-30-2:2016 specifies efficiency classes for variable speed rotating electric machines not covered in IEC 60034-30-1. The classification only covers machines designed for operation with sinusoidal fundamental

[2] Technical Specifications are often published when the subject under question is still under development or when insufficient consensus for approval of an international standard is available (standardization is seen to be premature).

current that are not designed to be operated direct on-line (grid), for example permanent magnet synchronous machines with and without additional reluctance torque, sinusoidal reluctance synchronous machines and synchronous machines with DC field windings.

More recently, the recognition of the importance of the potential energy savings achievable by addressing the energy efficiency of the entire motor system, instead of regulating individual components, has led to the development of standards that tackle this complex subject [22]. In the industry sector, efficiency improvement measures for electric motor systems would help to avoid nearly 3100 TWh of electricity consumption by 2040, cutting industrial electricity demand growth by nearly half when compared to a “business as usual” scenario. All these measures are cost-effective, being based on energy savings alone, and are designed to use technologies that are readily available today.

The use of VSDs for process control, matching the output to the demand of the process, can lead to substantial energy savings in particular in centrifugal fluid motion applications where the power varies with the cube of the speed (e.g. centrifugal pumps and fans). However, the VSD also introduces its own losses and, as referred before, leads to additional losses in the motor. Therefore, the analysis of VSD-fed motor applications needs to include these losses, measured or calculated at the different speed-torque points of operation.

To support the introduction of regulations at system level, IEC has developed the IEC61800-9 standard based on previous work carried out by CENELEC at European level (EN 50598 series). This standard has two parts:

- IEC 61800-9-1:2017, Adjustable speed electrical power drive systems - Part 9-1: Ecodesign for power drive systems, motor starters, power electronics and their driven applications - General requirements for setting energy efficiency standards for power driven equipment using the extended product approach (EPA) and semi analytic model (SAM) [23];
- IEC 61800-9-2:2017, Adjustable speed electrical power drive systems - Part 9-2: Ecodesign for power drive systems, motor starters, power electronics and their driven applications - Energy efficiency indicators for power drive systems and motor starters [24].

In Figure 53, the boundaries of the electric motor, complete drive module (CDM; i.e., VSD), power drive system (PDS = CDM + motor), motor system, driven equipment (DRE, which includes the mechanical transmission and the load machine), and extended product (EPR = PDS + DRE), as set out in the IEC 61800-9 standard, are shown.

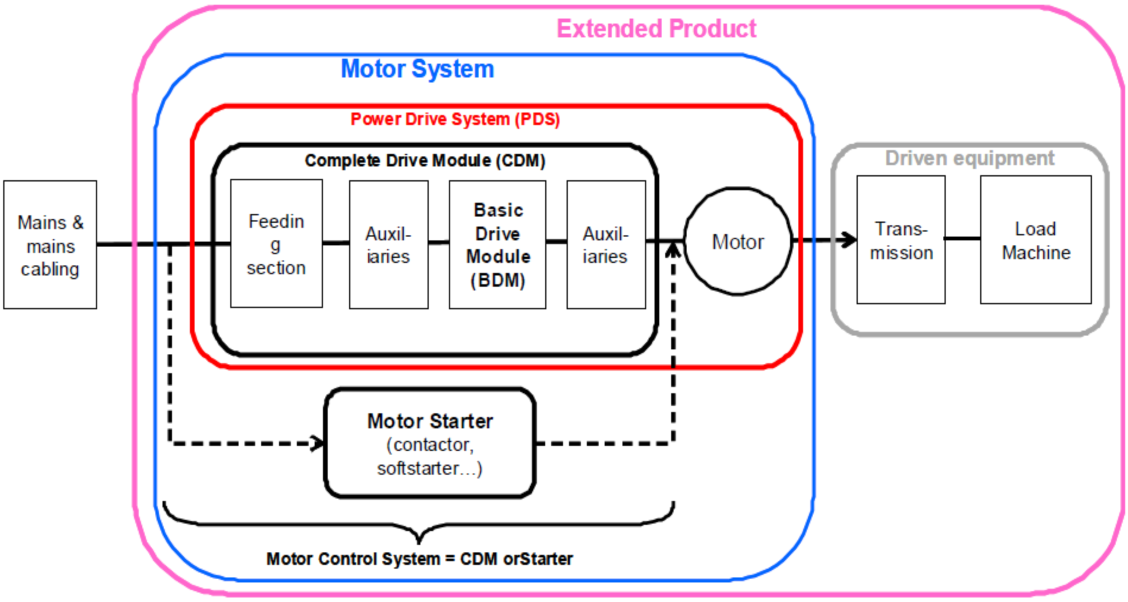


Figure 53 Boundaries of the complete drive module, power drive system, motor system, driven equipment, and extended product, as set out in the IEC 61800-9-2 ed.1.0 standard . Copyright © 2017 IEC Geneva, Switzerland. www.iec.ch

Since electric motors controlled by a variable speed drive can operate with variable speed and variable torque, it is important to test their efficiency performance in variety of load conditions.

The IEC 61800-9-2 standard defines different boundaries for the level at which the efficiency (or losses) are dealt with within its different parts (Figure 54).

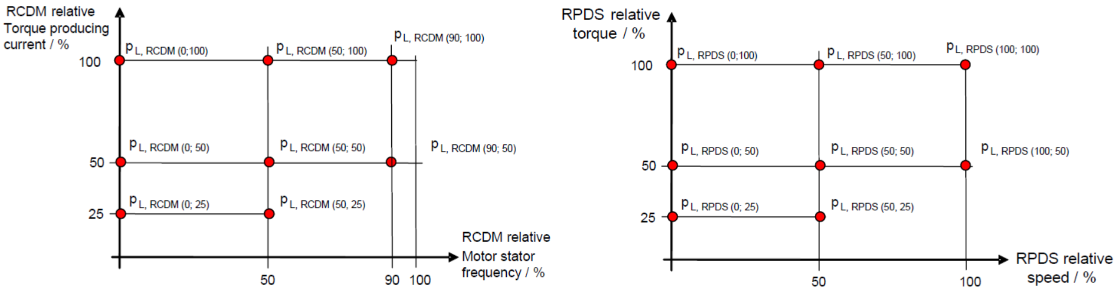


Figure 54 Illustration of the operating points (shaft speed and torque) for the determination of the relative losses of the Complete Drive Module (CDM) and Power Drive System (PDS) as set in IEC 61800-9-2 ed.1.0 [7]. Copyright © 2017 IEC Geneva, Switzerland. www.iec.ch

Part 1 of IEC 61800-9 standard specifies a methodology to combine the motor system data with the driven equipment data, in order to calculate the system energy efficiency for the whole application (extended product). The system efficiency is expressed by an Energy Efficiency Index (EEI) for a defined duty (load-time) profile. It allows the direct comparison of different motor systems, and to perform optimization at system level, by selecting the most efficient drive + motor + driven equipment combination.

Part 2 of IEC 61800-9 standard defines efficiency classes for the CDM and PDS. Because motors driven by VSDs are meant to be operated mainly at part load, eight operating points for testing are given, for the CDM and PDS, as shown in Figure 3. This operating points are defined by the pair of values (% of rated frequency; % of rated torque) in the case of CDM and (% of rated speed; % of rated torque) in the case of PDS, where the percent frequency corresponds to the ratio between the actual supply fundamental frequency and the rated supply frequency of the motor, the percent speed corresponds to the ratio between the actual shaft speed and the rated speed of the motor, and the percent torque corresponds to the ratio between the actual shaft torque and the rated torque of the motor. For the CDM, losses are measured at 90% of motor rated frequency to avoid overmodulation in the voltage-source inverter PWM output. For CDM classification purposes, only the losses at the operating point (90; 100) are considered, hence, the energy efficiency classes are defined based on that single operation point.

Reference values for the losses of the reference motor (RM), reference CDM (RCDM) and the reference PDS (RPDS) are laid down for the eight operating points defined in Figure 49 and efficiency classes are defined for the PDS and for the CDM relative to these reference losses. The losses for the RM are based on the IE2 class as defined in 60034-30-1. For the CDM, the standard defines three classes, namely, IE0, IE1, and IE2, and a reference value for losses corresponding to IE1 class is defined for each power size. If the CDM has 25% more losses than the reference value, it will be classified as IE0. If it has at least 25% lower losses than the reference, it is classified as IE2, as shown in Figure 55.

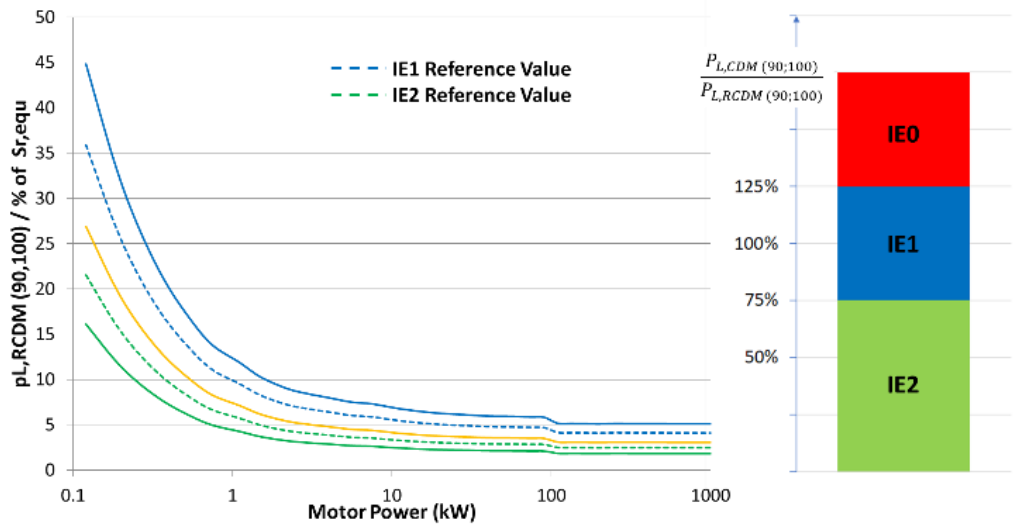


Figure 55 Efficiency levels and classes for CDM /VSD classification defined in the IEC 61800-9-2 standard.

For the PDS, a similar reasoning is applied, again with three classes, namely, IES0, IES1, and IES2, with IES1 as the reference class. The distance to the reference losses is only 20%. IES energy efficiency classes are defined based on the single operation point (100; 100).

Additionally, for the analysis of a particular extended product or PDS, all eight load points, a subset of these eight points, or the actual load points of a known application, can be used. For example, points (100; 100), (100; 50), (50; 25) (Figure 56 a)) can be used to estimate the losses in quadratic-torque applications such as centrifugal pumps and fans, while points (100; 100), (50; 100), (0; 100) (Figure 56 b))are used for constant-torque applications (e.g. conveyer belts, hoisting machines, and extruders). For constant-power applications, such as winders and winches points (0; 100), (50; 50) and (100; 50) (Figure 56 c)) can be used. The standard also specifies the extrapolation procedure to calculate other intermediate points. For a more accurate analysis of an individual application, the actual operating points of a PDS (speed; torque) can be used, as well as the duty-cycle profile (load ratio as a function of time) [25].

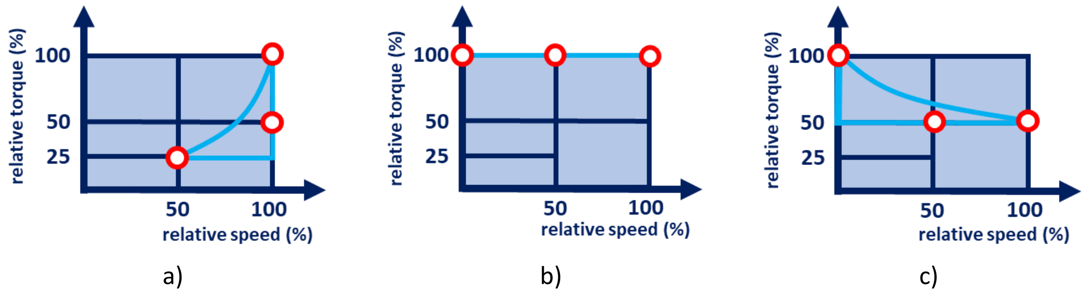


Figure 56 Relative speed-torque points used for efficiency analysis of common applications

5.1 Existing energy efficiency regulation

Recognition of the important contribution of electric motors to the global electricity consumption has led to the introduction of MEPS in most industrialized countries. Mandatory minimum efficiency requirements have proven successful because a price premium is not easily accepted in industry even when the payback is short.

Governments issue MEPS usually based on the efficiency classes for Direct-on-Line (DOL) motors defined in IEC 60034-30-1.

An overview of the AC three-phase induction motor efficiency voluntary agreements and regulation around the world is presented in Figure 57.

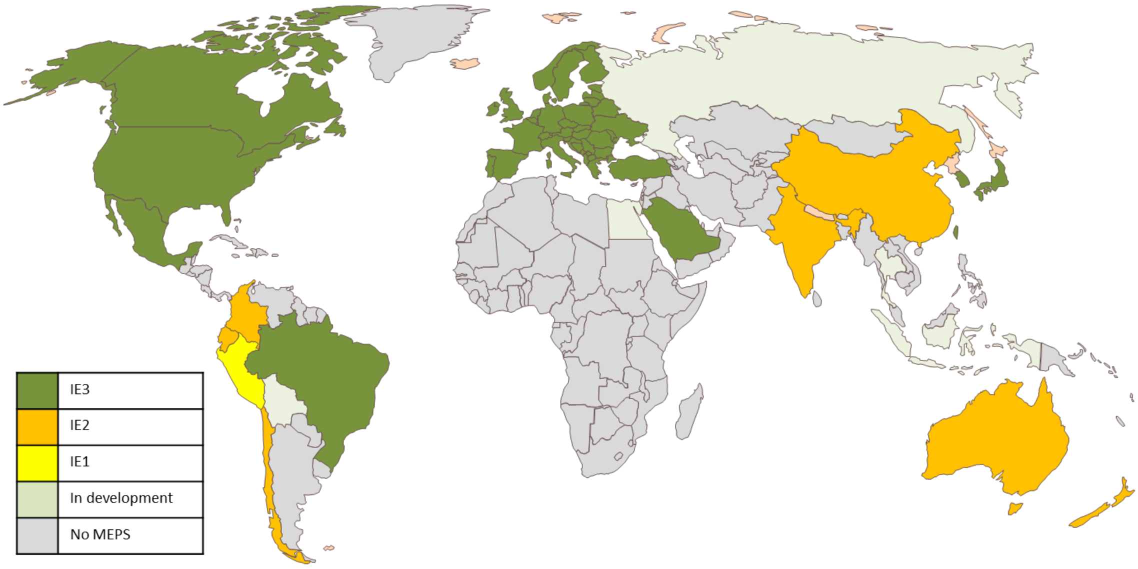


Figure 57. Overview of Minimum Energy Performance Standards (MEPS) Worldwide (Integral Polyphase Induction Motors)

First introduced in the USA and Canada in 1997, MEPS for electric motors were gradually introduced in other countries targeting induction motors of the medium power range (between 0,75 kW and 375 kW with small variations depending on the country) and are now converging at the IE3 efficiency level. IE2 is often used as a stepping stone towards the IE3 level (Figure 58) to allow manufacturers some time to adapt to the market.

Over 40 countries, representing 80 per cent of global electricity use in motor systems , have now regulated the energy efficiency of electric motors in all continents but Africa, with Latin America presenting some delay when compared to other regions.

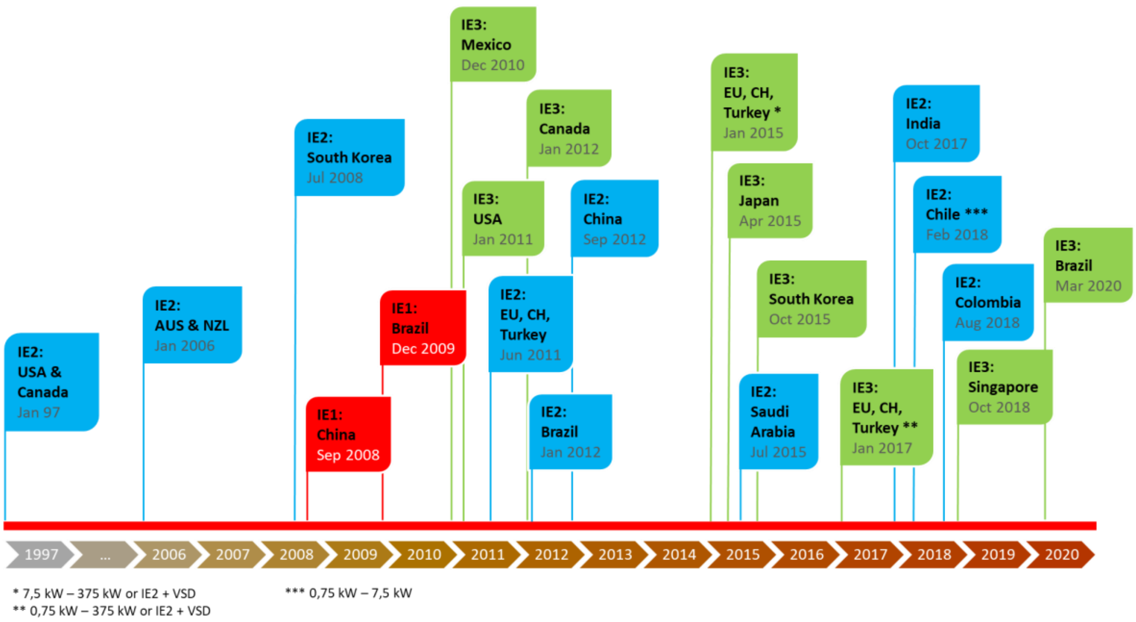


Figure 58 Timeline of global Minimum Efficiency Performance Standards for electric motors

The European Union has recently gone a step further, introducing MEPS at IE4 class level for motors in the 75 kW-200 kW power range, starting from 2021. For the first time, efficiency requirements for variable speed drives (VSDs) were also introduced, at the IE2 class level [26]. The VSD efficiency classes are defined in the IEC61800-9-2 standard.

The introduction of MEPS has pushed the market towards higher energy efficiency motors, helping to overcome identified barriers such as lack of information or split incentives, whilst simultaneously removing the worst products from the market [28]. However, electricity is the world's fastest-growing form of end-use energy consumption, especially among the emerging non-Organization for Economic Cooperation and Development (non-OECD) economies. Figure 59 shows that motor system's electricity consumption is growing fast, and is projected to almost double by 2040, even with motors being targeted by energy efficiency promoting policies.

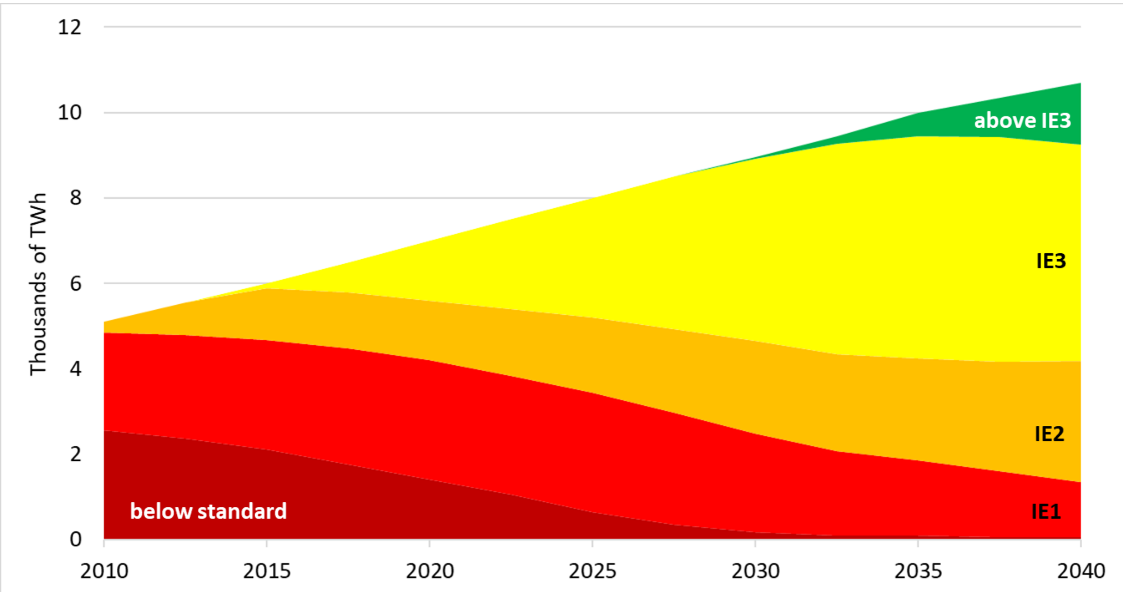


Figure 59 Global industrial electricity consumption by motor efficiency class in the New Policies Scenario[3] [29] © OECD/IEA 2017 World Energy Outlook, IEA Publishing. License: www.iea.org/t&c

Regulation in most developing and emerging economies is still missing and poses a serious risk, as motor manufacturers may use these non-regulated markets or regions as a market for their lower efficiency products. Since motors have a very long lifetime, it is possible that these inefficient products may still be in use more than 20 years from

[3] The New Policies Scenario reflects the way that governments, individually or collectively, see their energy sectors developing over the coming decades. Its starting point is the policies and measures that are already in place, but it also takes into account, in full or in part, the aims, targets and intentions that have been announced, even if these have yet to be enshrined in legislation or the means for their implementation are still taking shape. The climate pledges, known as Nationally Determined Contributions (NDCs)1, that are the building blocks of the Paris Agreement provide a rich and authoritative source of guidance for this scenario.

the time they are sold. On the contrary, early adoption of MEPS for electric motors will lock-in future electricity savings as the economy develops and improve the competitiveness of the economy by freeing capital from energy costs to other profitable investments. Likewise, the uptake of different policy options could play an important role in motivating the early replacement of old electric motors, with significant economic and environmental impacts. Examples of such policy options are:

- Financial Incentives
- Energy Management Programs
- Energy Audit Programs
- Raising Awareness and Information Provision

5.2 The Extended Product Approach

The current practice, with the exception of certain clean water pumps in the USA and water circulators in other countries, is to regulate the efficiency of individual motor system components, disregarding their interaction and best combination. However, the best approach is to determine and classify the efficiency of the EPR [13], considering the complete integration and interaction of the PDS, mechanical transmission (e.g. gear, belts, or direct coupling) and driven end-use equipment (e.g. pump, fan, or conveyor), as shown in Figure 60.

Some small products (e.g. circulator pumps, exhaust fans, and cooling compressors) include the motor, the VSD, and the end-use equipment (pump, fan, compressor, etc.) into one integrated package manufactured by one producer. This facilitates efficiency testing since direct input-output method can be easily applied, with the EPR efficiency equal to the mechanical power output divided by the electrical power input (in %). However, most of the times, motor systems are only assembled at the end-user site, most of the times impossible to physically test them. On-site tests are sometimes possible but are never as precise as tests carried out in laboratories in a controlled environment and repeatable conditions.

For this reason, a model for the determination of the losses of a motor system or a driven equipment is specified in IEC 61800-9, called a semi-analytical model (SAM). This IEC standard only covers electrical/electromechanical components (i.e., motor, VSD, motor starter), disregarding the mechanical components (i.e., mechanical transmission and load machine) that are dealt with by the International Organization for Standardization (ISO).

IEC 61800-9-1 specifies a generic approach for determining the energy efficiency of an extended product, that can be used to develop energy efficiency determination procedures for other non-electrical components. As such, the extended product approach (EPA, Figure 60) specified in standard IEC 61800 9 can only be used to determine the losses of the electrical/electromechanical components of the motor system. The losses of the mechanical components need to be obtained from other sources such as the related ISO standards or product manufacturers.

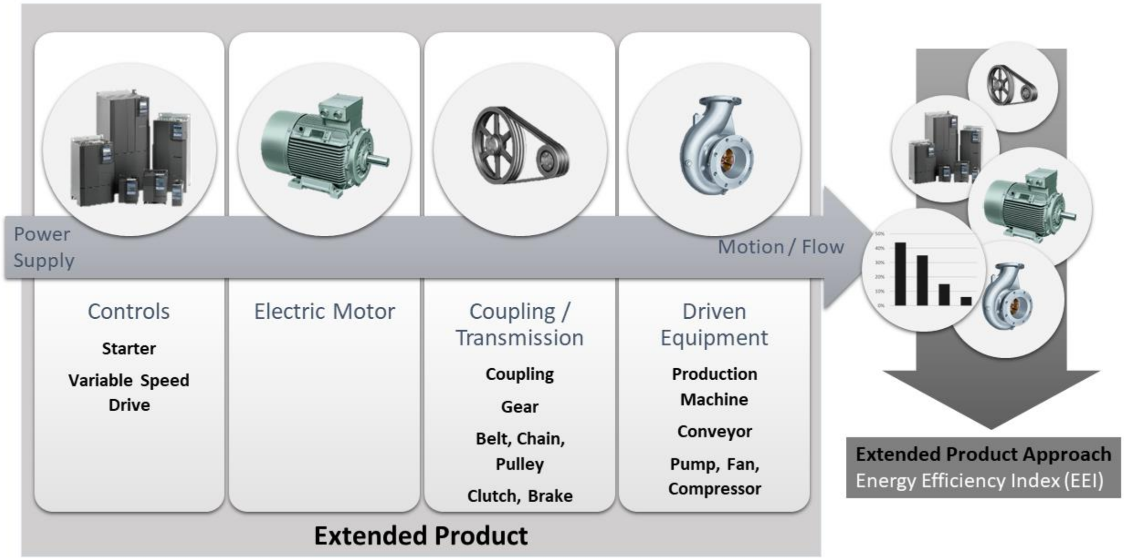


Figure 60 The Extended Product Approach.

The method can be used to determine the energy efficiency of the motor system for a particular application, taking into account the time spent at the different operating points (speed-torque). To calculate the EEI, the following inputs need to be known:

- Characteristics of the application load, namely, the torque or power as a function of shaft rotational speed, and the working time or fraction of time of each operating point (duty cycle), including standby mode.

- Power losses of components (Motor, CDM, end-use equipment, auxiliaries) at the operating points required by the application. Power losses are used instead of efficiency because they take into account particular conditions such as standby consumption (no-load condition, in which the efficiency is zero).

With this information and using the methodology specified in the standard, the user will be able to estimate power losses (PL) of the motor system and EPR at standardized operating points (OP) or the actual load points of a given application, as well as to calculate the Energy Efficiency Index (EEI) of the EPR for the given application.

Figure 61 illustrates the procedure considering a typical load profile of pumps used in heating, ventilation and air conditioning (HVAC) systems. The EEI allows the user to compare the efficiency of different combinations of components for a given application. Furthermore, the EEI will allow for the setting of energy efficiency labels and MEPS for EPRs as is the case for pumps in the US.

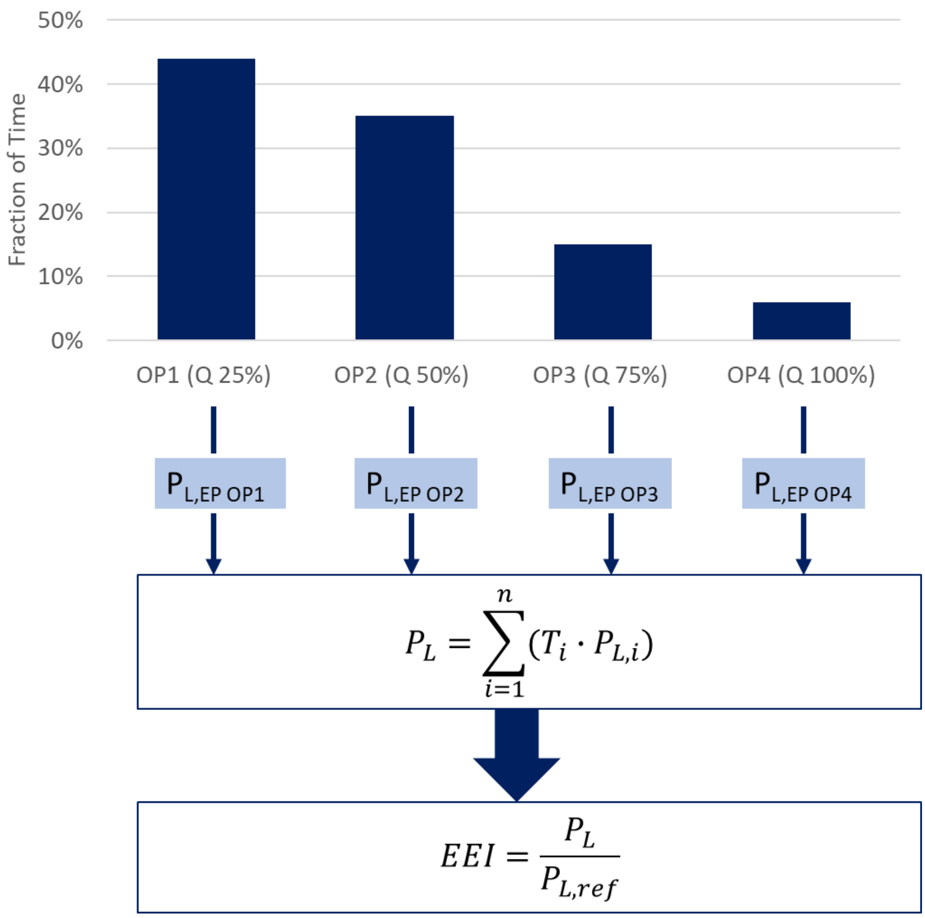


Figure 61 Example of application of the Extended Product Approach in typical load profiles of pumps used in heating, ventilation and air conditioning (HVAC) systems.

Beginning January 27, 2020, clean water pumps sold in the USA must have a Pump Energy Index (PEI) rating of not more than 1.00 as outlined in the Energy Conservation Standards for Pumps established by the USA [REF]. The PEI must be displayed on the pump rating plate. The same approach is being undertaken to establish similar regulations for the minimum efficiency of other motor products, namely fans [REF]. For the measurement of pump energy consumption and the calculation of PEI, a methodology was defined in cooperation with pump manufacturers and the Hydraulic Institute (HI). Building on this methodology, the HI has gone one step further and developed an energy efficiency labelling program (HI Energy Rating Program) [REF].

The label, as shown in Figure 62, also provides an Energy Rating (ER), which can be used to quantify energy savings potential. Multiplying the ER, in percentage, by the motor rated power (kW) results in power savings compared to the baseline.

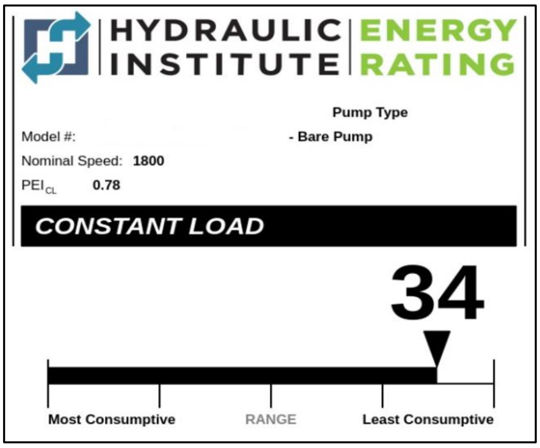


Figure 62 Example of USA Hydraulic Institute Energy Rating label for pumps.

5.3 Incentive policies and Programmes

Besides the implementation of legal binding standards for efficiency of electric motors, a number of initiatives have been put into practice with the purpose of increasing the penetration of efficient electric motors and their drives. Experience of many energy saving initiatives around the world shows that the most successful programmes are based on a mixture of technical information and financial incentives [33].

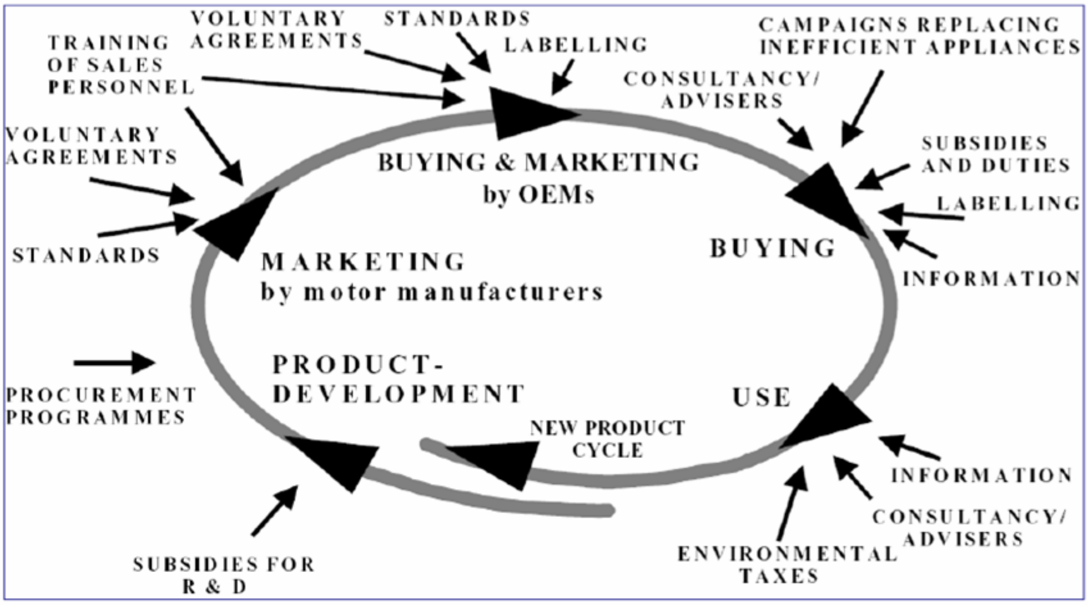


Figure 63 Policy instruments to reduce obstacles to diffusion of high-efficiency electric motor systems along the product cycle [34]

Most of the programmes implemented worldwide are based on common elements of which some examples are given:

Labelling

As stated above, there are a number of labelling schemes in place for motors with efficiency beyond minimum standards: NEMA Premium (US), Voluntary High

Performance Standards (Australia), IE3 (Europe), Grade 1 Motors (China). The purpose of these labelling schemes is to increase the visibility of products that exceed minimum energy-efficiency requirements and to educate consumers. Labels provide a highly visible and easy way to identify high performance equipment.

Training / Education

Some countries have training programmes in place directed at technical personnel – typically plant engineers, maintenance engineers, occasionally production personnel or energy managers. These will also be the individuals who will identify and then win funding for energy saving projects. Promotional/educational materials and schemes are available that address their differing needs at each stage on the way to implementing successful energy saving projects:

- Becoming interested in saving energy
- Receive sound technical information on energy saving options
- Identify possible energy saving projects
- Write and present proposal(s)
- Implement project(s)
- Estimate energy savings made

A selection of materials is provided, from short and simple introductory brochures through to guides giving much more detailed technical information needed to satisfy more experienced personnel.

Guidelines on the application of energy-efficient motors and drives are also widely available relating not only with motors but also with the system they are included in. These guidelines vary in complexity and some can be very detailed dealing with particular applications such as pumps, fans, compressors, etc.

Raising Awareness

Various techniques are used, including:

- Advertising
- Trade Press releases
- Direct Mail, Newsletters
- Conferences
- Workshops

Case studies

The best case studies of real life energy savings show not only all the benefits, but also any problems, giving confidence to readers that the stories are real and not simply omitting to mention important practical considerations. These case studies not only inspire others to do similar work, but can help both equipment suppliers to sell their products, and give personnel who will have to allocate funds a great deal of comfort that the technologies represent a sound investment of company funds.

Calculation Aids

Calculation aids, such as software, can give better estimates of possible energy savings. However, in practice, (particularly with VSD software), the input data is not known to sufficient accuracy to give particularly accurate answers. It does though give a good indication of likely energy savings, which alone is usually adequate to decide whether further consideration of an energy saving option is warranted.

Databases containing electric motor data are also available (EURODEEM, MotorMaster+) are an important information tool that allows users to easily carry out an evaluation of the best installation or replacement options, therefore helping to achieve electricity and money savings. Furthermore, they include motor inventory management tools, maintenance log tracking, efficiency analysis, savings evaluation, energy accounting, and environmental reporting capabilities.

Financial Incentives

Rebates are now seen primarily as a short term measure to help stimulate the market for energy saving products, which (as in North America) was a very useful precursor to legislation on minimum motor efficiency standards.

Rebates have been successfully applied to energy efficient motors, where they are typically set to equal the price premium of higher efficiency motors. Some money also needs to be given to the distributors to encourage them to stock such a range of motors. While giving rebates direct to the user is attractive, giving it to the manufacturers allows for a very useful “gearing” effect of the value of the rebate through the sales chain. Inevitably some EEMs will be purchased where the running hours are insufficient to give a good return on investment, but overall it is hoped that the scheme will give a good return, and in particular will stimulate interest in EEMs.

Rebates have also been given for VSDs, but this is a bit more involved. Most VSDs are sold for non-energy saving reasons, and so systems need to be put in place to give confidence that users are using them in approved applications only. It is likely that some form of assessment of the energy savings potential will need to be made, and if this involves proper power monitoring over a representative period, (perhaps a few days) will involve the potential equipment supplier in a lot of expense. Having received a detailed energy saving assessment, the company will then naturally seek several quotes to ensure best value for money, and so equipment suppliers may be reluctant to participate. Rebate schemes giving a reduction of perhaps 50% off the cost of a VSD are good for stimulating general awareness, but will still require similar levels of authorisation for funding, and so the increase in demand may not be huge. A key point relating to rebates for VSDs is that they will encourage users to focus on the price of VSDs, but the falling prices and resultant changes in the market of VSDs means that instead users should be encouraged to look for the quality of service and technical support. The long term effect of rebates for VSDs needs to be clearly carefully considered in order to ensure a sustainable change in the market [35].

Low interest or interest free loans are another tool used as an incentive to increase the market share of energy efficient equipment.

Capital allowances schemes are also in place which allow for the reduction of the tax payable, as an incentive for investment in energy efficient equipment. A certain percentage of the capital asset's cost is allowed as capital allowance during the accounting period in which it was purchased.

Several Utilities and equipment suppliers have tried schemes in which equipment (usually VSDs) is paid for from the energy savings, effectively giving a no cost route to purchase. While this sort of scheme is apparently very simple, in practice many schemes have failed because of the difficulty in agreeing the exact terms of agreement. In particular, there may be disagreement over the true level of energy savings due to changes in the pattern of use, or arguments over the appropriateness or accuracy of measurements. When in schemes such as this there is a very close focus on actual energy savings made, additional care must be taken to ensure that very reasonable estimates of energy savings are made, and it is sensible to slightly underestimate savings in order to help avoid later disputes.

Other Financial Tools

Bidding – Essentially an auction where electricity users bid the lowest price for rebates on electricity saving measures. Here motor users will be competing not only against each other for funds but also against other projects.

Penalties – Various forms of taxes on electricity bills to help improve the attractiveness of energy saving measures.

6 Motor Systems Energy Assessments

A Motor Systems Energy Assessment is an excellent starting point for understanding which motor systems offer the best opportunities for saving energy. It will:

- Identify some “quick wins”, low hanging fruit that require little further investigation.

- Identify some systems which with a short investigation within the motor systems assessment can give sufficiently accurate information make an investment proposal.
- Identify some systems that would justify a more detailed Fan, Pump or Compressed Air system Opportunities Assessment.

The main steps needed to carry out a Motor Systems Energy Assessment are summarised in the next figure.

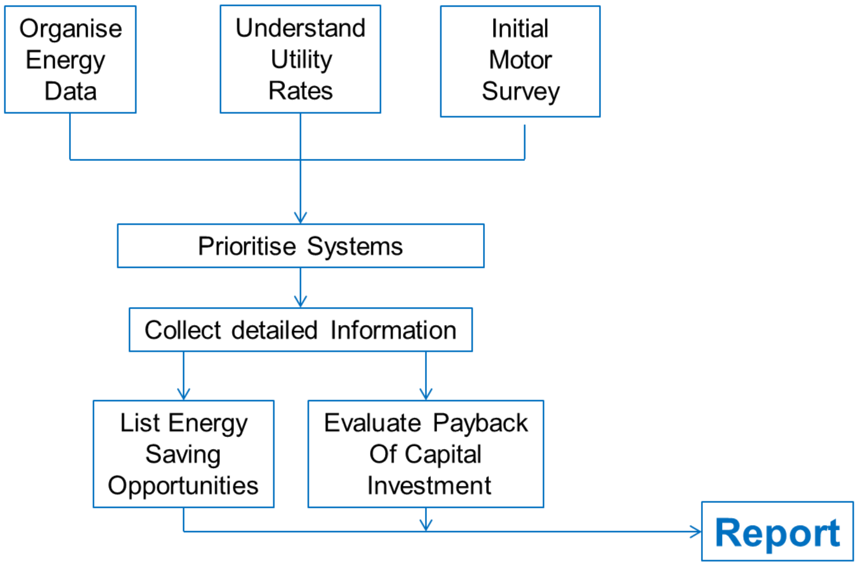


Figure 64 Main steps of a Motor Systems Energy Assessment

Remember: Look, Listen and Ask Questions. No Question is too obvious!

Instruments – are they believable?

Energy use - what exactly is it measuring?

Maintenance history – are there any hidden skeletons?

Problem machines – what clues might operators unknowingly have?

6.1 Sector Motor Use Information

By looking at the results of previous studies of motor use in your type of plant, good clues can be given as to both where the big energy using motors are, and what the best opportunities are. This will greatly help in the next stage of the EMS audit.

Key electricity consumption data from the plant shown in the electricity invoice for at least a typical month (ideally invoices should be available for one whole year) should be collected: Contracted power, peak power, energy consumed during peak hours, energy consumed during intermediate hours, energy consumed during off-peak hours and the reactive energy.

The motor systems installed in each production line should be characterized by:

- type of end-use (e.g. pumps, fans, compressors, conveyors, mixers, etc.)
- power range (concentrate efforts in motors with a power equal or larger than 0.75 kW).
- Control method used

If possible, identify through company records the age distribution of the motor stock, since older motors are generally less efficient and more prone to failure and should, therefore be a priority.

A table should be prepared for each type of motor end-use, showing nameplate power, efficiency, peak current, hours of operation, age of motor and process control method used.

A more complete information collection should also include:

- **driven load** – type, efficiency, power and speed rating, manufacturer and model;
- **system effects** – flow restrictions, valves, dampers and inlet and outlet conditions;
- **process load requirements** – flow, pressure, temperature, speed and hours operated;
- **control methods** – automatic, manual, measuring devices and operating techniques.

Information can be gathered from:

- nameplate data on each component in the system;
- manufacturer's specifications and performance charts;
- production records, utility bills, operations charts showing power consumption, flow rate and pressure for a one-year period;
- data on each process or piece of equipment using resources from the system;
- process and instrumentation diagrams including the control system strategy;
- field measurements.

6.2 Select Motor Systems to Consider

To reduce the time for the audit to something manageable, it is a good idea to pick just the largest rated 50-100 motors on your site, comprising perhaps 20 systems. This list should then be refined by calculating the actual annual energy use for each of these motors, which will also take account of both running hours and percentage load:

Annual energy use = NamePlate Power (kW) x Running Hours pa x Load (%)

Where the load is not known, a default value of 67% is *a useful average. (This actually understates energy use in that it ignores actual motor efficiency, but for this first screening* is *quite adequate).*

Once the motor systems have been ranked by energy use, the energy conservation opportunities can be evaluated for each.

6.3 Prioritising your time

Where not to look:

- Process equipment *(Value of throughput too high and plant already fine tuned for the process)*
- Critical processes *(Risk of unexpected problems unacceptable)*
- Small equipment *(Energy use too small to justify detailed investigation or implementation)*
- Equipment scheduled for replacement *(Financial payback unattractive)*

Where to look

- Big equipment (over 50 kW)
- Older motors which tipically have less efficiency
- Equipment with long operating hours (at least 2000h/year)
- systems that have blowers, pumps, fans and compressors, especially where flow is controlled by throttling devices or can be made variable.
- Long down times
- Support equipment
- Problem equipment

6.4 Evaluate the Opportunities

For each motor on the list, consider the following 5 Energy Saving Areas:

- Switch the motor off when it is not needed.
- Slow it down. (Control Motor speed)
- Reduce the motor losses (Improve motor efficiency)
- Reduce transmission losses.
- Reduce losses in the driven system

6.5 Estimate the Energy Saving Potential

Make a very rough estimate of the energy savings and cost of implementing the identified opportunities.

Detailed Evaluation of Energy Saving Potential

Evaluated opportunities should be split in to the following action categories:

• Some opportunities will be "quick fixes" which require little funding and give very good paybacks.

• Other opportunities will be uneconomic and should be immediately rejected.

• Opportunities which have marginal economics, may require further refinement, which will include collecting more data.

6.6 Motor Load Control.

The first item to check is whether the power or work supplied corresponds to the actual load requirements. The most cost-effective and rational measures are those aimed at preventing unnecessary running of the motor at no load. Therefore, a first set of questions concern the proper load matching, distinguishing between simple and trivial switch off measures and continuing with more targeted measures for controlling variable loads.

Can it be switched off when it is not needed?

Compare the actual running time of the motor with actual period of time for which it is doing useful work - for instance:

- Holidays
- Weekends
- Nights
- Starts too long before shift
- Finishes too long after shift
- Lunch and mid-morning/afternoon breaks

In these cases energy savings can be made by fitting time, proximity or load switches.

Running continuously where loads are irregular

- Batch operations
- Irregularly used services
- Switch off one of a bank of machines

Where a motor runs irregularly, multiple machines **or** a smaller machine could be fitted to suit the load conditions.

Is there a varying demand?

Perhaps demand varies with throughput, outside temperature, product type etc?

The greater the time at lower flows, the better the economics.

Typical applications for VSD control:

- Water circulation pumps
- Cooling tower fans
- Extract fans
- Boiler motor systems
- Secondary refrigeration pumps
- Variable volume ventilation fans

The potential savings from fitting VSD's will depend on number of operating hours and duty cycle. A good example is when a pump motor load varies between 100% and 10% full load power and the time at lower loads is greater than 50%, additionally if the pump operates for more than 5,000 hrs each year. Full monitoring of potential energy saving and payback is recommended.

The use of VSDs often gives other benefits in terms of product quality, reduced maintenance etc, and so a full evaluation of these savings may encourage the fitting of VSDs.

Other uses for VSD's include:

- Stirrers - can be good savings but very dependent on application
- Conveyors - some savings from reducing internal losses
- Air compressors
    - Screw compressors. Very marginal as retrofit, but could make good sense if bought with integral VSD.
    - Centrifugal compressors. Leave alone.
    - Reciprocating compressors. Possible, but significant spending may be not desirable on these older machines.
    - Can the motor be slowed down or is the equipment just over-sized for the application?

Modern motors are designed for maximum efficiency at 75% full load and between 50-100% there is only a minimal variation in efficiency. However, a significant reduction in efficiency occurs at loads of 25% full load or less, and it is at this level that serious consideration should be given to fitting a smaller motor.

The Power-cubed rule that applies to centrifugal fans and pumps, in low head systems, means that if the speed can be reduced by just 20%, then energy savings of up to 50% can be made. These are therefore the applications to target at the initial screening stage. If the motor drive chain can be slowed down, important savings can be obtained.

Direct process plant such as conveyors, machine tools, and packaging units are usually optimised for production efficiency, and so there is usually little scope for speed control. Indeed, these are the applications where you are most likely to find speed controls already fitted. Installing and commissioning new equipment can cost expensive downtime and lead to temporary reject product while being commissioned, and so it is really worth leaving these applications for later.

Is there occasionally a requirement for much more or much less flow?

The speed may be acceptable for most of the time, but during sometimes it could be much less (e.g. night-time extraction requirements) or much more (e.g. emergency faster extraction requirement). Multi-speed machine might be appropriate.

Reduce the motor losses (efficient electric motors)

It is unusual to know the efficiencies of motors on site, especially if there are many different brands as is often the case on OEM equipment. Before finding efficiency information, it is suggested that consideration be given to leaving the use of Higher Efficiency Motors (HEMs) and Motor Replace/Repair as a single site-wide policy action. Since most measures can only be implemented when a motor needs replacing anyway, this realistic approach greatly reduces the initial audit time without missing out on significant economic energy saving measures.

Sizing is generally of lesser practical importance, and "Off the shelf' units such as compressors, fans and many pumps are unlikely to be grossly over-sized. It is custom designed installations where excess safety margins are most likely to lead to over-sized motors.

Coupling and Transmission Losses

If the motor is not direct-coupled, review the type of transmission and how well it is maintained. Drive belts and gearboxes are the main source of efficiency loss.

6.7 Driven equipment & systems

For each motor, consider the efficiency of the equipment and system that it is driving. For anything more than the simplest opportunities, it is just sufficient to identify the simple and obvious opportunities, more advanced options will need a specialist, perhaps as part of a Fan, Pump or Compressed Air system audit.

6.8 Assessment Report

The results and recommendations of the motor system energy assessment should be summarized in a final report. The report should include:

- a description of the facilities and their operation,
- individual measurements of major energy consuming systems,
- a description of all recommended measures with their specific energy impact, implementation costs, additional benefits and payback.

7 Taking Measurements

Taking measurements takes time and so costs money. Some energy saving opportunities are so obvious that there is little point in obtaining any actual energy consumption data. But if you do need more data to gain more certainty on a possible measure or to put forward a more convincing business case, then there are various options available.

Field measurements can be an invaluable source of information for better decision making when optimising your motor system. The energy savings achieved are dependent on a number of factors, such as:

- motor size,
- annual hours of use,
- load factor,
- efficiency gain (at the load point)

Field measurements are necessary to establish the load imposed upon an existing motor by its driven equipment and then determine motor efficiency at its load point.

In a three-phase power system it is necessary to measure the following at each motor:

- phase-to-phase voltage between all three phases,
- current values for all three phases,
- power factor in all three phases, and
- operating speed of motor and driven load.

Equipment necessary for these measurements include:

- Three-phase power analyser (ideally), with a set of probes covering different current ranges (e.g. 20A, 200A and 1000A)
- voltmeter or multimeter
- clamp-on ammeter
- power factor meter
- tachometer

Meters should be of adequate quality to read true RMS values.

Modern three-phase power analyser can, simultaneously, make readings of voltage, current, power, power factor, energy, harmonics, frequency and transients, and also have logging capabilities which allow for the recording of parameters over time.

Figure 65 Three-phase power analyser, with current clamps and voltage probes on the right.

Electrical measurements can also help identify problems with the quality of the power supply such as:

- Voltage and current unbalance,
- Low power factor
- Harmonics

Voltage unbalance

Ideally, the voltages that you measure in each phase of a three-phase system should be the same. This is also true for current measurements.

Voltage unbalance (VU) is given by:

$$\%VU = \frac{max.\,voltage\ deviation\ from\ the\ avg.\,voltage}{avg.\,voltage} \times 100$$

Voltage unbalance can cause voltage notching and excessive current flow in one or more phases going to the motor, which can cause tripping of the motor drive's current overload fault protection, leading to unnecessary downtime. Voltage unbalance also reduces motor efficiency.

Low power factor

Low power factor reduces the efficiency of the electrical distribution system both within and outside of your facility. Low power factor results when induction motors are operated at less than full load.

Harmonics

The 50 or 60 Hz frequency of the voltage supplied by the utility is called the fundamental frequency. Some electrical loads (such as computers, controls, VSDs, lighting) can cause other frequencies to appear in your measurements. These other frequencies, which are multiples of the fundamental (so 120 Hz, 180 Hz, and so on for a 60 Hz fundamental frequency), are called harmonics.

The power at the service entrance of your facility will usually be low in harmonic frequencies. Inside your facility, however, harmonics may be high if there are a lot of harmonic-generating devices in the facility.

Although motor drives can be affected by harmonics, they are often the source of harmonics that affect other devices in the facility. If you detect significant levels of harmonics in your drive measurements, you may need to consider adding filtering to block those harmonics.

There are many electrical tests and investigations that can be used to determine the condition of key constructional factors. Some tests can be done while the motor is still in operation, 'online', while some require the motor to not be in use, 'offline'.

Offline testing allows for more comprehensive testing to be done. Tests include surge test, winding resistance/coil resistance testing, meg-ohm test, polarization index testing, high potential test and step voltage test. Testing the state of the windings by the winding resistance and insulation resistance test is a good way to begin, as any other test will be affected by the winding condition.

Online testing is done whilst the motor is operating, and while tests are more limited, they do have the advantage of reflecting real life operating conditions.

Speed measurements are critical as speed may change with frequency, load and belt slip. A simple tachometer is a contact type instrument which can be used where direct access is possible. More sophisticated and safer ones are non contact instruments such as stroboscopes.

(a) (b)

Figure 66 Contact tachometer (a) and stroboscopic tachometer (b)

Furthermore, measurements can help to determine process load requirements – flow, pressure, temperature, speed, etc.

7.1 Load Estimation Techniques

To accurately estimate the savings of replacing an existing motor with a more efficient, correctly sized one, first there is need to know the actual load of the existing motor.

Motor mechanical loads may be estimated through using input power, apparent power, or speed measurements. The input power method gives the most reliable results and is preferred.

a) Input power method

With measured input power taken from hand-held instruments, and information from the motor nameplate (efficiency and rated power) it is possible to calculate the three-phase input power to the loaded motor and the motor load by using the following equations. The accuracy of the method drops when load is below 40% since efficiency sharply significantly drops below that value.

$$P_{input} = \frac{P_n}{\eta}$$

$$Load(\%) = \frac{P_{measured}}{P_{input}} \times 100$$

Where,

P_{input} – is the nominal input electrical power at full load

P_n – is the mechanical nominal power (rated on the nameplate)

$P_{measured}$ – is the measured input power

EXAMPLE:

Name plate data:
Rated kW of Motor = 30 kW
Rated Amps = 55 A
Rated voltage = 400 V
Name plate efficiency = 92%
Name plate speed = 1440 rpm

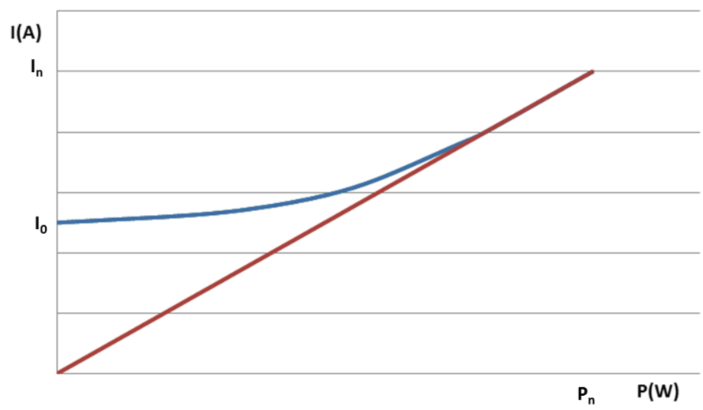
Measured Data
Measured speed = 1460 rpm
Input load current = 33 A
Operating voltage = 415 V
Input power = 20 kW

a) Input power method

P_{input} = 30/0,92 = 32,6 kW
Load = 20 /32,6 x 100= 61%

b) Voltmeter-Ammeter Method

This method is less accurate than the previous method, but does not require a power meter, since on the current and the voltage need to be measured. Also called the "apparent power method" it is recommended for values from full load down to 50% full load. It relies on the fact that the amperage draw of a motor varies approximately linearly with respect to load, down to about 60% of full load, as shown in Figure 67. For lower loads the current drops much less than the load because the magnetization current to create the rotaing magnetic field is almost constant, leading to a overestimation of the mechanical power.



I_0 – No load Current
I_n – Nominal Current

Figure 67 Motor current variation with load

Load is estimated using the formula:

$$Load\ (\%) = \frac{V_{measured} \times I_{measured}}{V_{rated} \times I_{rated}}$$

c) Tachometer Method

If the rotor speed is near synchronous speed, the motor has a small load. If the rotor speed is close to nominal speed the motor is near full load. The rotor slip is proportional to the load, if the voltage is kept constant.

This simple method only requires a tachometer and computes shaft output power as the rated horsepower multiplied by the ratio of measured slip to the slip expected when the motor is fully loaded, with a correction for the voltage variation. It is only applicable to induction motors. Load is estimated using the formula:

$$Load\ (\%) = \frac{Slip}{(S_{synch} - S_{nameplate}) \times \left(\frac{V_n}{V_{measured}}\right)^2} \times 100$$

Also called the "slip method", although this technique can provide a qualitative assessment of the motor load (e.g. underload, medium and close to full-load) the method has largely been discredited as a viable technique for estimating motor efficiency, because of the large errors it may infer. Potential errors include the rounding of the nominal speed in the nameplate and rotor speed variance among motors.

7.2 Efficiency Estimation Techniques

Ideally the maintenance engineer would like to be able to compare actual efficiency with that of the original condition. Unfortunately the formal test procedures

(IEC60034-2-1, Standard on Efficiency Measurement methods for low voltage AC Motors) involve a large investment in testing equipment. . Even if it was possible, the need to remove the motor from site to a test lab incurs a large cost and time, and so it is not a practical proposition.

However, the following two tests are a very useful indicator of motor condition that require no expensive apparatus, and are particularly appropriate for checking the condition of a motor following repair:

- The stator resistance gives a clear indication of the amount of copper used – showing clearly the use of conductor with a reduced cross sectional area.
- With the motor mechanically disconnected but energised, the no load active power can be measured, which will increase if the motor laminations are damaged. This implies the previous knowledge of the no-load current of the motor before repair. This value can estimated using the procedure described in the Figure 4, since the no-load power factor is very small (typically in the range 0.1 -0.15).

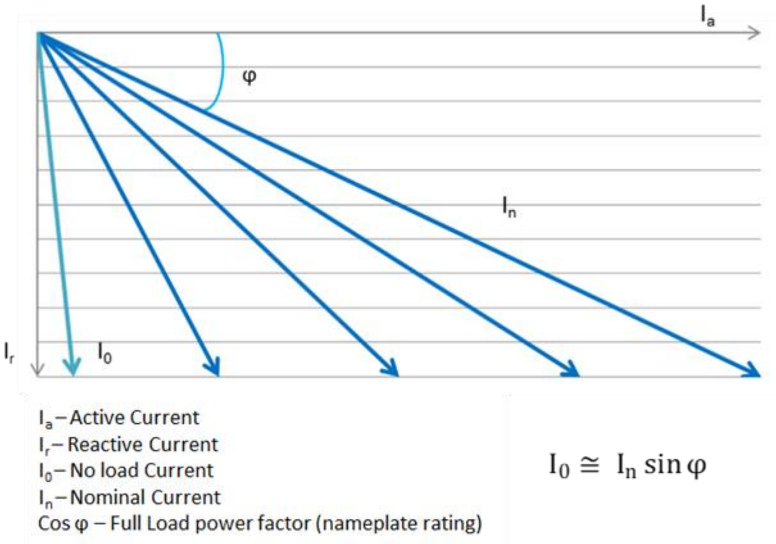


Figure 68 Contact Estimation of the no-load current I0 based on the nameplate data (Nominal current - In and power factor - cos φ). Source - ISR-University of Coimbra.

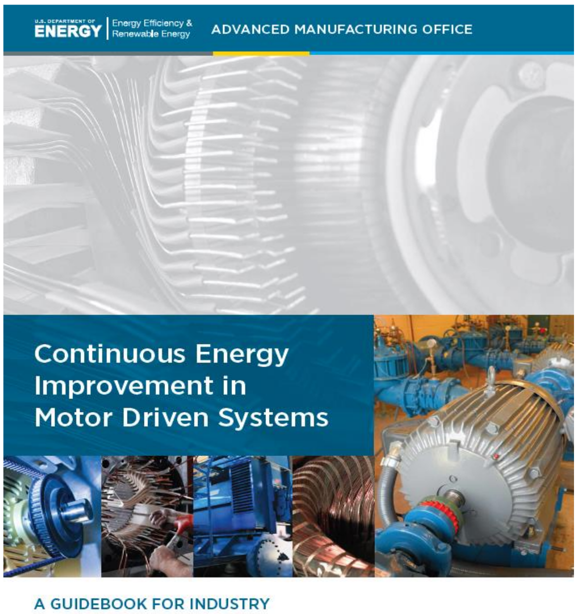
While measuring the actual efficiency of an electric motor is difficult and costly, simple tests to check for deterioration in performance after repair are useful as part of tracking the motor condition over its lifetime.

The IEC TC 60034-23: 2003 - Specification for the refurbishing of rotating electrical machines, which is soon to be replaced by IEC 60034-23: 2018 - Repair, overhaul and reclamation (expected publication date is December 2018), defines a minimum schedule of routine tests to be performed in order to evaluate the performance of the repaired motors. For induction motors, they include testing of:

- Resistance of windings
- Insulation resistance
- No-load losses and current
- Vibration levels

Nevertheless, the standard recommends that tests to prove performance should be agreed between user and the service facility, prior to the repair.

For further information, see Chapter 5 Motor Load and Efficiency Estimation Techniques, **Continuous Energy Improvement in Motor-driven Systems – A Guidebook for Industry,** United States DOE, Fev 2014 [36].



Safety Considerations

The following text is for general guidance only. You should only take measurements if you are competent to do so.

- Do not use handheld instruments above 600V.
- Use line workers gloves.
- Keep left hand out the way when attaching probes.
- Tie back loose hair or clothing.
- Beware of the unconnected ends of current transducers when connecting to a separate display device.
- Where possible, connect leads when the power is off.

- Periodically check that the leads and connectors are in good condition. If in doubt, throw them out.
- Use leads rated for the voltage.

Sensitivity of Motor Load to Operating Speed

Motor and driven-equipment speeds must be measured as closely as possible, ideally with a strobe tachometer. Motor speed is important because a replacement motor should duplicate the existing motor speed.

For centrifugal loads such as fans or pumps, even a small change in a motor's full-load speed translates into a significant change in load and annual energy consumption. Fan or "affinity" laws indicate that the loading imposed on a motor by centrifugal load varies with the cube of its rotational speed. When considering motor changes, it is useful to measure the speed.

Most energy-efficient motors tend to operate with reduced "slip", meaning that they work with a slightly higher speed than their standard-efficiency equivalents. This small difference - an average of only 5 to 10RPM for 1500-RPM synchronous speed motors - is significant. Just a small 20 RPM increase in a motor's full-load rotational speed from 1240 to 1260 RPM can result in a 3.5% increase in the load placed upon the motor by the rotating equipment. A 40 RPM increase can boost energy consumption by 7%, completely offsetting the energy savings typically expected from the purchase of an energy efficient motor. However, the greater speed means that the work is being done at a faster rate, and so providing that it is properly controlled, the expected energy savings will still appear.

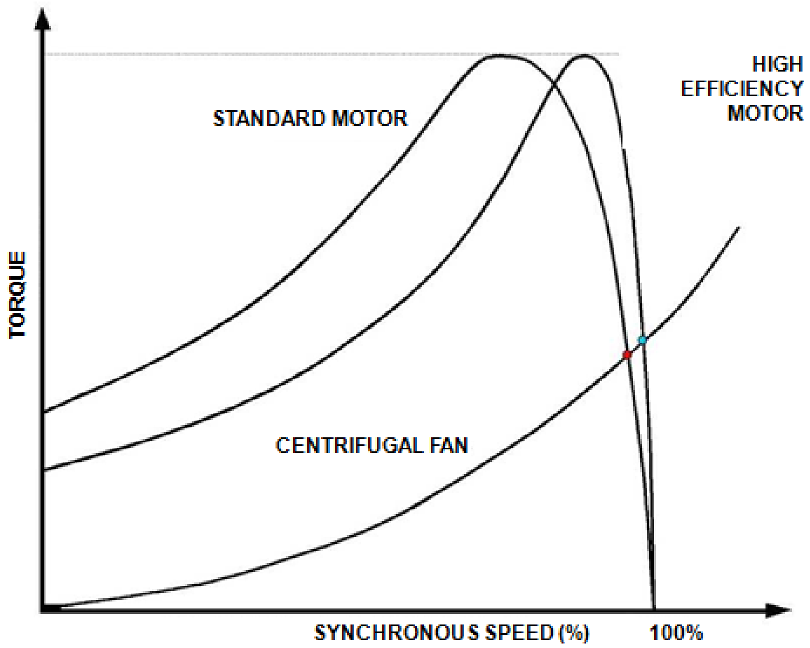


Figure 69 Standard and high efficiency motor Torque speed-curves

8 Energy and Maintenance

8.1 Benefits of Better maintenance

The primary purpose of maintenance is to keep equipment running at optimum performance and, at the same time, avoid premature failure.

A well maintained motor system will also bring energy benefits, such as:

- Use less energy.
- Be more reliable, and so reduce the energy and production costs of unplanned downtime.
- Give the option of extending an existing maintenance programme and related systems to identifying and maintaining energy efficiency options.

8.2 Motor Maintenance techniques

Preventive maintenance is the traditional form of maintenance but, recently, predictive maintenance has received increasing attention.

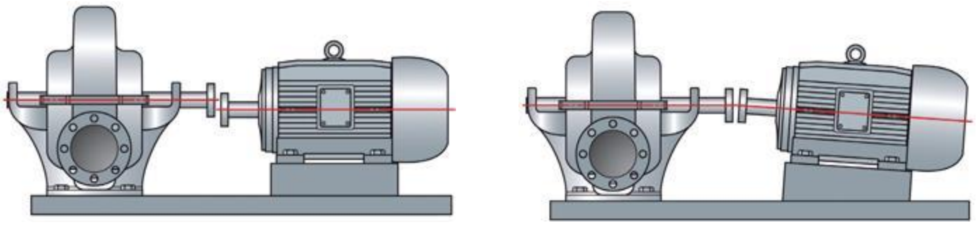
Preventive maintenance (also called planned maintenance or planned preventive maintenance) is driven by time, meter or event based triggering. Maintenance tasks that are undertaken during PM's are pre-determined based on a number of factors including experience, age, manufacturers recommendations etc. It is assumed that a machine component will degrade within a time period that is common for its type. Under a preventive management approach, the relevant parts will be removed, replaced or rebuilt on or before the expected failure point. For example, your engine oil in your car is proactively replaced at 10,000 miles.

Predictive maintenance is determined by the condition of equipment rather than average or expected life statistics. Essentially, this methodology tries to predict the failure before it actually happens by directly monitoring the machine during normal operating condition. In the car example above, rather than replacing the oil every 10,000 miles, using predictive maintenance methodology, oil samples are taken at regular intervals and the oil is replaced when it degrades beyond a certain point.

A comprehensive maintenance program contains elements of both predictive and preventive maintenance (PPM). Both involve scheduled actions to the motors and controls, as well as record keeping.

The most important items to check on a motor maintenance program are:

- **Dirt and corrosion**
  Dirty motors run hot - Heat reduces insulation life and eventually causes motor failure. Serious corrosion may indicate internal deterioration and/or a need for external repainting
- **Lubrication**
  Observe the bearings lubrication schedule. Improper lubrication shortens bearing life in many ways. Additionally, operating environment has a significant effect on lubrication requirements.
- **Mountings, Couplings, and Alignment**
  Incorrect mounting can lead to decreased efficiency and reduced service life. Correct shaft alignment ensures the efficient transmission of power from the motor to the driven equipment.



a) b)

Figure 70 Parallel misalignment (a) and angular misalignment (b) (source: http://www.flowcontrolnetwork.com/)

Figure 71 Modern laser alignment equipment (directindustry.com)

- **Transmission**
  Check for drive belt wear, and replace pulleys if needed. Check for belt tension use tension meter and belt wear using simple profile gauges. Maintain a gear lubrication schedule.

- **Heat, noise and vibration**
  Excessive heat is both a cause of motor failure and a sign of other motor problems. A change in noise or vibration can signal bearing problems, shaft misalignments, bent shaft, load imbalance.

Written records indicating date, items inspected, service performed and motor condition are important to an effective routine maintenance program. From such records, specific problems in each application can be identified and solved routinely to avoid breakdowns and production losses. Additionally, maintenance records can be used to collect information relevant to the energy management of motor systems.

Thermal testing and trending of temperature data, along with vibration analysis are examples of predictive maintenance techniques.

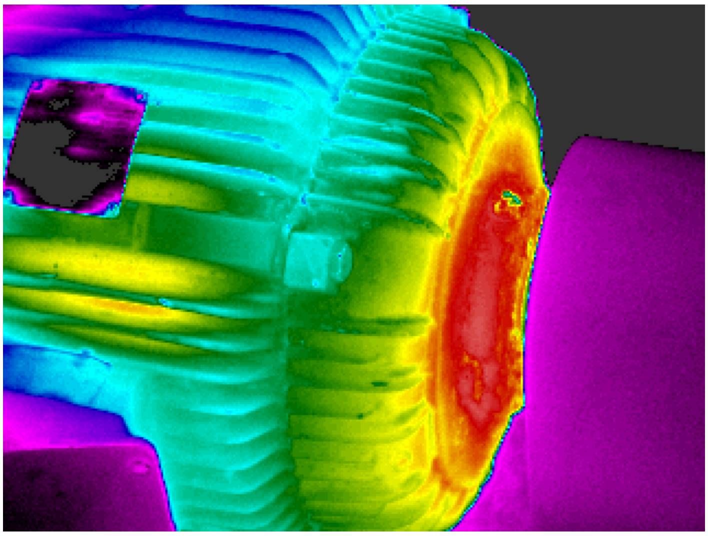


Figure 72 Thermal imaging

Temperature Monitoring

Understanding what exactly is a safe or normal operating temperature is essential but not always that easy. It will be influenced by several factors:

- Design of motor
- Ambient (local) temperature
- Load factor
- Ventilation method
- Voltage supply (voltage level, balance and distortion)
- Altitude

Even so, understanding when there is a temperature related problem is difficult, and so looking at the motor temperature history, or comparing with similar motors can be very helpful. Several potential problems should be looked for:

- Bearing over-heating, especially of the hotter Drive End, (the Non Drive End or NDE has the advantage of forced cooling).
- Local hot spots on the casing, identifying a stator winding fault (less frequent).
- For motors with VSD control there may be additional temperature stress due to both the higher harmonic content of the supply, leading to higher losses, and the reduction in forced cooling if operating at low speeds with high torque loads.

For larger machines, consideration should be given to installing permanent monitoring devices to continuously monitor critical areas such as the bearings and the stator windings. Options for sensors are resistance temperature detectors or thermocouples.

In a low voltage motor, an option is to fit thermistors that can be built in to trip the motor when the temperature increases above a certain point.

It is essential to regularly clean the motor to keep the ventilation paths clear, especially on open ventilated motors (Figure 7). Blocked ventilation is one of the most common causes of overheating of the machine due to restricted cooling. Dirt accumulation on the motor case itself and, in particular, around the cooling fins also contributes to decreased cooling capacity, which may lead to overheating and premature failure.

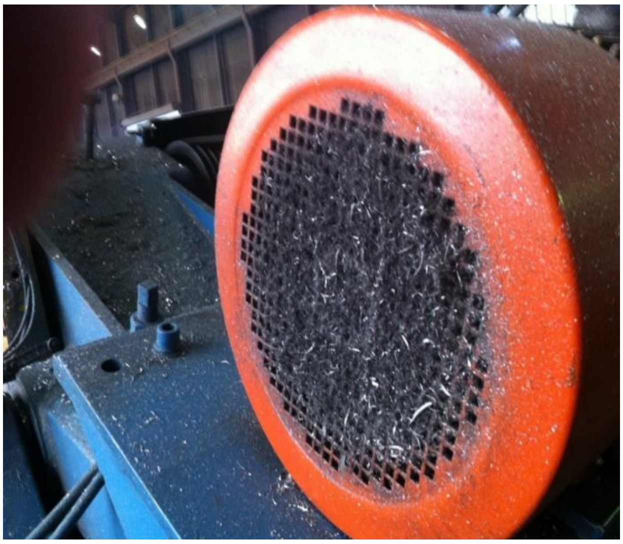


Figure 73 Partially blocked fan on an induction motor in a metal processing plant. (Atkins)

Vibration Monitoring

Full bandwidth vibration monitoring is a powerful way of understanding the condition of a motor, and can often be used to pinpoint the precise cause of the vibration by linking the frequency to the different moving components. It is even more valuable when considering vibration in complex systems where there may be a transmission and pump, fan or other driven component in the assembly. Both mechanical and electrical faults can be detected using this method of monitoring. Issues such as: bearing fluting, air gap variation, broken rotor bars and misaligned couplings can all be identified and remedied.

Permanent fixtures such as displacement probes and accelerometers may be attached to the motor in order for the vibration levels to be monitored at all times.

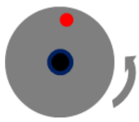
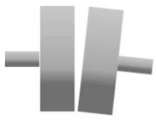
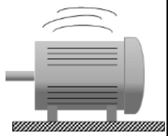
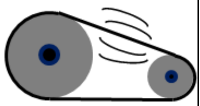
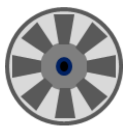
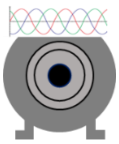
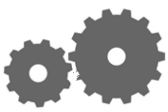
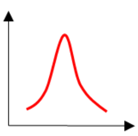
Low cost, amplitude only, vibration monitoring can quickly assess for overall condition, and is particularly successful at identifying bearing wear and damage. The increasing use of VSDs is leading to a decrease of the mean time between failures (MTBF) of the motor bearings due to the circulation of high frequency common-mode currents [5]. Repair shops and motor manufacturers are seeing an increased number of instances where bearings and connected equipment are being damaged by this electrical current circulation that can cause, for example, “fluting” in the races and “pitting” in the spheres, shortening the bearing and lubricant lifetime (Figure 9). For example, in Germany, it is reported that in VSD-fed motors, the bearings MTBF decreased from 7–8 years (typical lifespan in line-fed SCIMs) to 2–3 years due to the high-frequency bearing current activity [6].

Figure 9 Example of Motor Shaft Voltage and Bearing Current Damage [7], Source: Renown Electric

Measures to avoid this phenomenon should be implemented, such as insulated bearings (the inner or the outer bearing ring is covered with a ceramic coating) or using high performance ceramic ball bearings (more expensive, but longer lifetime), shaft-ground brushes or bypass shaft rings. Reducing the VSD switching frequency also contributes to reduce the bearing current activity.

The stator windings lifetime can also decrease significantly, namely in old motors, due to the high-voltage transients/surges impressed by Pulse-Width-Modulation (PWM) voltages generated by the VSDs.

Table 7 – Using a full frequency vibration analyser to identify which component is the source of vibration. Adapted from Pruftechnik – An Engineer's Guide - Making Maintenance Matter

POSSIBLE CAUSE	DOMINANT FREQUENCY	DIRECTION	COMMENTS
Unbalance 	1 x rotational frequency	Radial for dynamic unbalance; possibly axial	Vibration amplitude proportional to unbalance & rpm causes severe vibration.
Misalignment 	2 x rotational frequency	Radial & axial	Severe axial vibration and 2nd harmonic; best realigned using laser.
Bearing defects 	High frequency vibration	Radial & axial loaded position if possible	Use bearing enveloping diagnostic techniques or shock pulse to determine damage severity.
Machine  **Foundations**	Typically at one or more natural frequencies (transient vibration)	Radial	Natural resonant frequency of foundation or machine base-plate.
Belt vibration 	1 x rotational frequency	Radial	A strobe can compare pulley rotational speed and belt speed in order to identify belt slippage.
Blade pass frequency 	Number of vanes or blades x fundamental frequency	Radial	Vibration frequency represented by the number of blades multiplied by the shaft rotational frequency.
Electrical 	Line frequency, 50Hz or 60 Hz & multiples thereof	Radial & axial	Side bands may also occur at multiples of the rotational frequency. Vibration ceases when power is turned off.
Gear mesh defect 	Gear frequency equal to the number of teeth x rotational frequency of the gear in question	Radial & axial	Side bands occur from modulation of the gear-teeth meshing vibration at the rotational frequency, e.g. the input and output shaft speeds of the gearbox.
Component resonance 	Component's natural frequency	Radial & axial	A component's natural frequency coincides with an excitable frequency.

The following (free) commercial guides are highly recommended for the information that they provide, but UNIDO cannot recommend specific brands of equipment.

Thermal Imaging
Thermal imaging guidebook for industrial applications, FLIR, 2011
http://www.flirmedia.com/MMC/THG/Brochures/T820264/T820264_EN.pdf

Vibration Analysis
Making Maintenance Matter - Optimising plant availability using laser shaft alignment, vibration analysis and dynamic balancing techniques, Pruftechnik, 2002
http://www.pruftechnik.com/fileadmin/pt/Downloads/Brochures-Flyers_SPECIAL/Engineers_Guide_ALI_CM/EngineersGuide2012.pdf

On-line condition monitoring

The usefulness of spot condition monitoring of equipment is limited by the time intervals between tests. On-line condition monitoring overcomes this constraint by giving continuous information on machinery status.

The motor manufacturers will usually offer major and critical plant with built in sensors, most commonly power/current monitoring, temperature or vibration sensors. The availability of this technology has been expanding fast with the emerging Internet-of-Things (IoT) and the manufacture transition to Industry 4.0. Such on-line monitoring not only allows for real-time viewing of machinery status, but more importantly shows trends over time. With care, it is then possible to follow the condition of the machine as a function of plant operations, allowing identification of plant operations most likely to accelerate wear.

Should a sudden failure occur or a particular condition be reached (e.g. level of vibration or temperature), then the immediacy of the alert can prevent further damage.

Another advantage of on-line monitoring is that it avoids the risk with portable monitoring equipment of small differences in sensor position or firmness of mount (vibration monitoring) giving misleading readings.

Whilst on-line condition monitoring is the ideal way of detecting developing problems before they lead to failure, it is unlikely to be cost effective for less critical plant, even though its cost has been decreasing.

Nowadays, most modern industrial plants are implementing motor monitoring systems, following the “IoT” and “Industry 4.0” trends, which are becoming a standard. Continuous key operation data acquisition and record, including the actual motor load variation over the entire operating cycle, is very important for the users to make smart decisions regarding the motor maintenance or replacement, particularly concerning the best option when a motor fails and is oversized and/or has variable load.

On one hand, monitoring key data such as current, voltage, temperature and vibration, allows to apply motor condition monitoring techniques targeted to, for example, performance assessment, fault diagnosis and failure prognostics, i.e., preventive conditioned or predictive maintenance strategies can be implemented, reducing the costly unplanned downtime of the PDS.

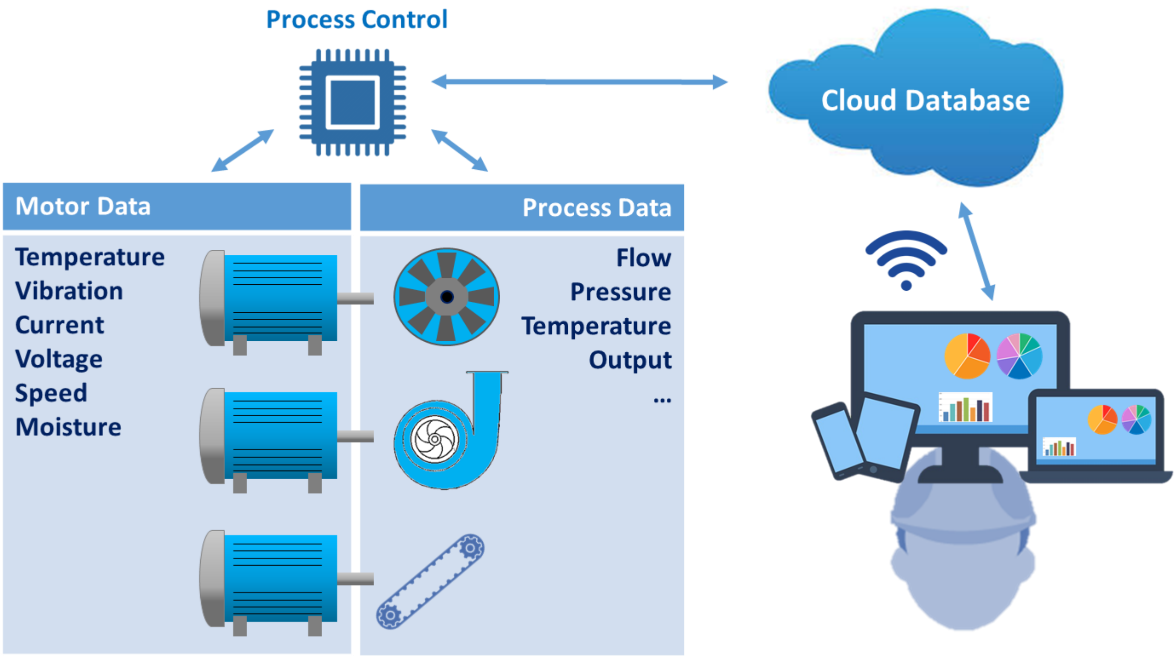


Figure 74 . Motor Systems Condition monitoring and the Internet of Things (Source: ISR-UC)

On the other hand, the continuous monitoring of current and voltage, allows to estimate the motor load cycle and supply condition, which is key data to know if the motor is oversized or has a variable load and, on that basis, decide if it should be replaced by another of different rated power, the connection mode should be changed, or it is advantageous to redesign the stator winding in order to match the peak efficiency with the dominant and/or maximum actual load level.

Furthermore, the continuous monitoring allows comparing the system performance before and after implementing a given measure and to provide evidence of the expected/claimed energy savings or benefits, including verifying if the motor is consuming the same energy after a repair/rewinding service.

Continuous monitoring is also important to identify abnormalities in the motor supply voltages or load prior to a fault or failure, in order to the user be able to take proper action to avoid repeating the same situation.

Nowadays, there are several commercial data acquisition solutions with wired and/or wireless communication interfaces to monitor three-phase motors.

If convenient, the collected data can be stored in an online database. Many companies specialized in large-scale maintenance services offer online big data analysis tools, incorporating deterministic and/or machine learning based algorithms to produce useful information for motor maintenance, relatively simple to understand by the end-user.

8.3 Maintenance Decisions Matter: An Alternative Approach to Stimulating Energy Savings

From an overall business perspective the productivity benefits of improved maintenance, including avoidance of the sometimes huge costs of unplanned plant failure, make it a higher management priority than energy efficiency As a result, industry is much more likely to spend money on maintenance than on energy savings activities.

Why Maintenance?

Finman & Laitner (2001) analysed 77 published case studies on energy efficiency, from which they identified 5 common non-energy saving benefits:

- Reductions in waste
- Reductions in emissions
- Reductions in maintenance and operating costs
- Improvements in productivity and quality
- Improvements in the working environment

Other, such as from saving space, reducing capital expenditure, improved public image, and improved worker morale.

Of the 52 case studies that attempted to put monetary values to these gains, the average payback fell from 4.2 years on energy savings alone, to just 1.9 years when all savings were taken account of. Although the high energy-only payback is distorted by the many case studies demonstrating newer and innovative technologies, the general result remains valid. A further paper, (Laitner et al. 2001) shows the results of ascribing monetary values to the non-energy saving benefits of possible energy saving actions in the US Iron and Steel sector. This showed that for the same payback criteria, taking account of the non-energy benefits doubled the savings that could economically be made. This is equivalent to additional energy savings of 1.9 GJ/ton of steel produced, or 170 PJ (1.6 x 1014 Btu) of potential savings across the whole sector.

Analysis of UK studies also shows that in many cases it was actually these non energy benefits that were the critical factor behind the decision to consider the project in the first place. This finding was one of the principal reasons behind the idea to try to implement an initiative that, instead of just promoting energy efficiency, would instead use the non-energy saving benefit of maintenance as the primary proposition, knowing that energy saving would follow through the back door.

Examples of Maintenance Issues Affecting the Implementation of Energy Efficiency Measures

There is much evidence from ongoing energy efficiency work to support the idea that an interest in maintenance is behind the adoption of energy saving practices, with the following selected to show the diversity of ways in which this occurs:

The European Copper Institute's long running UK campaign to encourage greater cable sizing to reduce power losses had been disappointing, but when the same measure was expressed as a way of reducing the incidence of plant failure through improving power quality, it became very successful, as it was now something of great and immediate interest to lots of companies.

While the economic arguments for higher efficiency motors in the UK is good, it hasn't been convincing enough to see a big change in the market. But promoting best practice to take account of what to do when a motor fails is of much more interest. It is therefore much more likely to lead to management attention being given to the running costs of motors and the importance of efficiency.

Many consultants have noted that having a site maintenance engineer accompany a consultant during a site energy savings opportunities assessment can give a much deeper insight into the true state of plant operation than anyone else. For example, a compressed air system that always gives enough air at the right pressure and adequate quality would be regarded as no trouble by the Production Department, but it's the Maintenance Department staff who will point out the need for more and more compressors or excessive maintenance effort needed to provide this service. More generally, pausing to stop and ask questions of everybody in a plant with an interest in a particular system, in particular any problems that it causes, can also help to identify all sorts of discrepancies in people's understanding of the requirements and performance of systems, and so can give an excellent clue as to energy saving solutions.

One of the key drivers behind the Europump/Hydraulic Institute guide to Life Cycle Costing (LCC) of pumping systems was the realization that energy savings alone were insufficient to make many people improve the design and maintenance of pumping systems. The basis of the Life Cycle Costing guide was that all directly attributable costs over the lifetime of an item of plant, such as purchase, maintenance, energy, spares, disposal etc. should be accounted for when designing a system. The success of this wider approach suggests that thinking beyond just energy saving is more likely to stimulate action. Interestingly, when analysing the impact of the work, it became clear that the rigorous engineering analysis needed to do a proper LCC calculation was too often being ignored either because of pressures of time or simply a lack of skills. We have seen this as a further stimulus to better educate personnel in maintenance and energy and their related costs, since these are usually the biggest unknowns in an LCC calculation.

Table 8 The Link Between Energy and Maintenance Savings

	Practice	**Result**
Motors	Rewinding	A good quality rewind will reduce efficiency by only 0.5 – 2.0%
	Lubrication	Over-lubrication can cause premature bearing failure and efficiency loss of up to 1%
	Shaft Alignment	Incorrect shaft alignment costs about $8/kW per degree of misalignment
	Belt adjustment	Belt drive efficiency deteriorates by 10-15% without regular adjustment
Compressed Air Systems	Fixing leaks	Typically reduces costs by 15-20% if controls are adjusted to accommodate the reduced volume required. Network zoning, removal of redundant spurs, and maintenance of connector & cylinder seals all reduce leakage
	Condensate drain traps	Electronic condensate drain traps are much more reliable, wasting less air than mechanical or manual traps
	Servicing	Regular servicing maintains performance and efficiency
Pumping Systems	Impeller maintenance	Maintaining impellers and coating pumps maintains efficiency. Pump condition monitoring equipment identifies the proper timing for pump refurbishment
	Speed control	Variable speed control reduces wear on the pump, bearings, and seals
	Variable speed drives (VSDs)	ASDs can alleviate water hammer and its effects, and can prevent cavitation in certain circumstances
	Valves	Jammed non-return valves waste lots of energy in parallel pumping systems
	Fixing leaks	Reduces water consumption as well as reducing energy consumption
Fan Systems	Filter cleaning	Dirty filters produce unnecessary pressure drop
	Duct cleaning	Dirty ducts create excessive friction, producing unnecessary pressure drop
	Blade maintenance	Worn and dirty fan blades reduce efficiency
	Dampers	Worn or inoperable dampers increase energy consumption
Steam Systems	Boiler maintenance	A poorly maintained boiler loses 5-10% efficiency
	Oxygen control systems & ASDs on combustion air fans	Reduces the need to regularly monitor and adjust burner controls, thus saving fuel, reducing emissions, and reducing fan power consumption

	Fixing leaks	Leaks and faulty steam traps waste energy
	Pipe insulation	Maintaining the integrity of pipe insulation minimizes steam heat loss

Finally, Table 8 lists for five key items of industrial plant some of the common actions that have both a maintenance and energy saving benefit. The amount of overlap shows that there are many practical maintenance actions that have a direct energy saving benefit, and so help to justify the promotion of maintenance as a way of also saving energy.

The Costs of Failure

The cost of maintenance failure explains why there is so much management interest in the subject, and a readiness to spend money to improve plant performance. As an example, Table 9 below shows the typical costs of an unplanned stoppage in a selection of industries.

Table 9 The Costs of Unplanned Equipment Outages [37]

Industry	Typical financial loss per stoppage
Computer centre	$825,000 (Euros 750,000) per event
Financial trading	$6,600,000 (Euros 6,000,000) per hour
Glass industry	$275,000 (Euros 250,000) per event
Semiconductor production	$4,180,000 (Euros 3,800,000) per event
Steel works	$386,000 (Euros 350,000) per event
Telecommunications	$33,000 (Euros 30,000) per minute

In addition to these costs, feedback from UK Maintenance seminars finds that management is increasingly concerned with maintaining equipment properly in order to comply with health and safety regulations, where the costs of a successful prosecution are a big deterrent to poor practice. Poor quality or late delivery of products resulting from equipment failure can jeopardize future business, and so also came across as being a major additional concern.

Overall Equipment Effectiveness

The measure most commonly used by management to assess the performance of a plant compared to the ideal is that of Overall Equipment Effectiveness (OEE), and so it is interesting to see how energy efficiency relates to the parameters measured by this. OEE takes account of all the direct costs of poor plant performance, and is usually defined as:

OEE = Availability (Breakdown losses + Set up and adjustment losses)

x Performance Rate (Idling + Minor stoppage losses)

x Quality rate (Rework losses + Start up losses)

If the bracketed maintenance costs look familiar, it is because they also represent common sources of energy loss. These hidden energy costs can be substantial, and these and other sources of energy losses due to plant failure are described in more detail in Table 10.

Table 10. The Energy Costs of Plant Failure

Effect of unplanned breakdown	Related energy cost
Temporary reduction of output during breakdowns	Core or background energy needed to maintain essential services is spread across less output, and so the specific energy consumption rises.
Start up losses	A lot of energy is lost during the warm up time of high temperature processes.
Alternative methods for re-gaining production used	Less efficient methods of production may be used, perhaps using older equipment or involving additional transport costs.
Loss of product during warm up time	Some processes have to produce scrapped product while they are "warming up".
Energy used in part processing the product is lost	Much energy may have been expended in getting a product to near the end of a production process, and this energy will be wasted.
Disposal of damaged product	There may be energy costs involved n the physical disposal of scrap product.
Emergency repairs made to re-start plant ASAP	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.
Rework costs	Additional energy used in re-working spoiled product.
Time lost for less urgent work	Time that could have been spent on energy saving work is lost

Table 11 gives a simple breakdown of the causes of plant breakdown, and the remedies to eliminate the causes. Again, the direct energy efficiency benefits of better maintenance in the top 85% of causes are apparent.

Table 11 How Plant Breakdowns Can Be Eliminated [38]

Percentage of breakdowns / stoppages	How they can be eliminated
> 40%	Refurbishment and hence restoration of equipment to its standard conditions
> 20%	Application of daily asset care checks and best practice routines of operation
> 25%	By application of regular and relevant condition monitoring and planned maintenance
> 15%	By designing out physical weaknesses in the equipment

How Maintenance Best Practice Can Help Overcome Non-Economic Barriers to Energy Efficiency

So far it is just the clear links between energy efficiency and maintenance that have been shown. But in addition to the commonality of technical measures, there are other aspects of maintenance best practice that help to overcome some of the common noneconomic barriers to energy saving projects being implemented:

Gaining the Support of Others Who Might Benefit from a Project

Talking to other staff, such as maintenance and production personnel, who are also familiar with the item of plant, is a very good way of identifying other benefits. But in addition, by making them feel involved and being able to identify what is in it for them personally, they are more likely to support the proposal.

Integrating Energy Saving Actions with Planned Maintenance Shutdowns

On equipment that runs for weeks or months between scheduled stoppages, the cost in lost production means that shutting down plant to fit and commission energy saving equipment can only be done if planned ahead as part of a scheduled shutdown.

Integrating Regular Maintenance and Energy Saving Databases

A list of all key equipment should be at the heart of a maintenance management programme, and is an excellent basis for an energy management programme.

Integrating Routine Maintenance and Energy Savings Checks

Routine checks on equipment such as checking for leaks, monitoring temperatures/pressures etc. are core elements of both maintenance and energy saving campaigns. The implication is that the person doing these should be aware of both reasons for undertaking them, and where appropriate modify the details of the work to maximise all energy saving and maintenance benefits.

Reviewing Site Service Demands

Expansion or contraction of plant output can quickly lead to a mismatch between the provision of site services and the actual demand, and is a common cause of inefficiency. A better match minimises the costs of maintenance both through better use of existing plant, and through the avoided costs of maintenance on plant to supply capacity that is no longer needed. The periodic re-appraisal of what site services are actually needed should therefore be part of maintenance and energy saving best practice.

Design for Maintenance

Designing equipment so that it can be easily maintained, or not need maintaining at all, can reduce energy consumption.

A Way of Working

An organization that has a right approach towards maintenance, both by having a maintenance management system that works, and by having the right employee attitude, is in a much better position to implement a successful energy saving campaign.

Better Maintenance Is Free

Analysis of case studies from the 2002 UK Maintech conference (Maintech 2002) shows that in all five of the detailed examples cited, in addition to reaping the benefits of better maintenance, overall maintenance costs actually went down. This is because the additional expenditure on better monitoring and preventative maintenance was more than compensated for by the reduction in expensive fire-fighting maintenance. With so many companies looking to further squeeze maintenance budgets, the idea that you can do better with less expenditure is a very attractive promotional idea. The overall operational benefits from these studies are summarised below:

Summary of Savings achieved in practice from improved Maintenance Practices

Lever Faberge increased production capacity by $2.4 million/year (£1.5 million) via an increase of OEE of 110%, while reducing maintenance costs by 31%.

British Aerospace increased OEE on machinery from 26% to 65%, improved quality by 10%, reduced downtime by 10% and halved spares costs in another area.

Blue Circle Cement reduced breakdowns by 67% and saved almost 20% on their maintenance budget.

Imperial Chemical Industries (ICI) reduced maintenance expenditure by 20% while increasing throughput leading to a reduction of maintenance costs/tonne of product of 30%.

Unilever achieved a 30% improvement in productivity whilst reducing maintenance costs by 30% and also substantially reducing defects.

9 Motor Repair

Best Practice Motor Repair

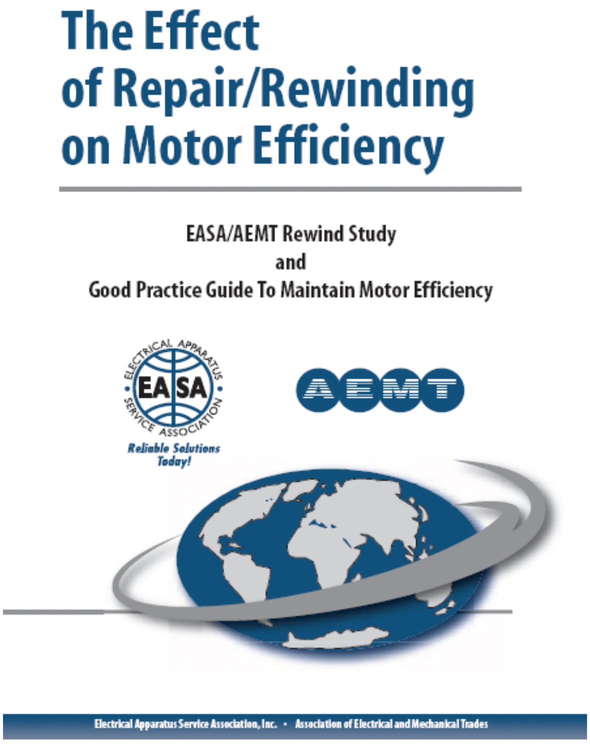
Repairing an induction motor will typically lose 0.5-2.0% of efficiency, and you will miss the opportunity to upgrade to a new, more efficient motor.

A first action is to always use a quality motor repairer that adheres to international best practice. This is described in the Good Practice Guide section of the following publication:

The Effect of Repair/Rewinding on Motor Efficiency (EASA/AEMT)

Management and Energy Managers. Executive Summary (P1-3)

Maintenance personnel and motor repairers. Good Practice Guide (P2-3)



When motors fail, there is also the opportunity to change to a more efficient motor, so gaining additional energy savings. But the economics of this are highly site and motor dependent, and so a Motor Management Policy is suggested so that it is easy to make the best decision and that maintenance personnel are authorized to sometimes spend more up front in order to yield longer term energy savings.

Deciding on the conditions determining whether on failure a motor should be repaired or replaced is a complicated issue. This entails balancing factors such as the cost of the motor, price to repair/replace, money lost from outage, any special mounting requirements, operational conditions, estimated performance and actual measurements recorded. Early replacement of motors can also be a strategy to consider, with reduced payback times and additional advantages (e.g. energy savings, improved reliability, reduced maintenance).

Considerations when fitting a new motor

There are many practical considerations to be taken account of when considering the swapping to a new motor:

- Mounting hole positions and size.
- Length of motor.
- Starting current.
- Slip (and hence running speed).
- Shaft height
- Shaft diameter

Improving an old motor

A good repairer, and informed user, can alter the stator windings slightly to give for example better efficiency or slightly higher starting torque. But this depends on having a detailed understanding of the load, and should only be contemplated by experienced personnel.

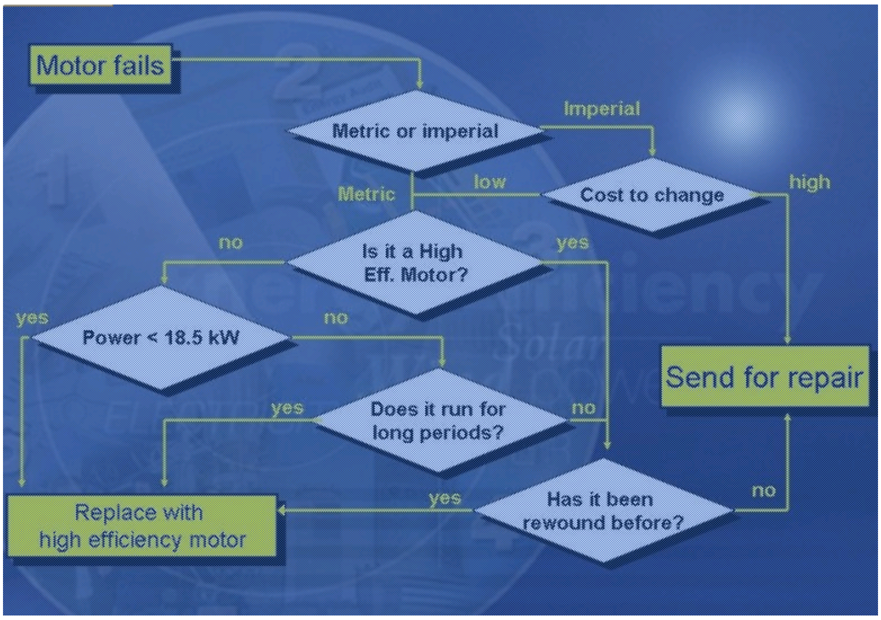
A Motor Procurement Policy Template

Ideally an organisation should have a simple procurement policy that is understood by all. It will comprise some guidelines like the example below:

Our Motor Procurement Policy
• Below ___ kW we replace the motor • Above ___ kW we repair the motor, unless it has already been rewound twice. • Between ___ kW and ___ kW we may repair or replace, depending on the duty.

The simpler it is, the better. Some flexibility is needed, but not such that it is easy for personnel to just override the policy whenever convenient!

Some suppliers suggest decision charts such as that below (ABB), but you should always be sure that the chart reflects your particular circumstances.



Identifying a quality repair shop is difficult, but the following are some indicators to take account of:

- What motors can they rewind?
- What wire gauges do they have in stock?
- If limited, there may be compromises on stator resistance or number of turns.
- Is there a controlled burn-out oven? And what other techniques do they use for winding removal?
- How experienced are the employees?
- What training do the employees receive?
- Is there a core tester to check for core damage?

10 How to win approval for energy efficiency projects

Because, Energy Efficiency is perceived by as discretionary, less important because of low value, technically risky it sometimes has a low place on the management priority list.

Therefore, just identifying a good technical opportunity and preparing a good financial case isn't enough to make it happen.

Some common objections are:

We are not convinced because…

…the problem is not clear

…we don't understand your solution

…there is no evidence it would work

…we disagree with your assumptions.

We like the project, but…

…installing it sounds like it would be disruptive

…we are not sure how long we are going to retain this building/process/equipment

…the workforce would not accept it

…we do not have any money available to fund the project

…the necessary staff resources are needed for other work

…one of us has got a better idea

…why haven't you done anything about this issue before?

Who do you need to influence?

Whoever you are pitching to, think carefully what their considerations will be, what their motivations are, and the format that they want information in.

Can you engage them in the process early to aid their understanding and secure their support?

Often you will need support from other colleagues impacted by your projects, and so take care to also consult them with the same level of detail.

Building your case

The developed business case must present clear objectives, not only financial but, if possible, worthwhile additional benefits:

- Monetised specific savings goals.
- Lower maintenance.
- Improved production processes.
- Improved environmental performance.
- Enhanced corporate reputation.

These objectives must be supported by an appropriate analysis of the costs, benefits, and risks, and accompanied by an implementation timetable. Savings estimates made by third-parties (e.g. equipment suppliers) should be verified. Presenting optimistic savings in the first-place can yield disappointing results and impair your credibility to implement future projects.

A thorough risk analysis should be carried out and all the risk and downsides to the project should be part of the business case, as well as the strategies to control or mitigate those risks.

Identifying supporters

Identifying somebody who can support your work is invaluable to help smooth the way for winning funding.

They will not only help you portray your project in the best light, but also bring an understanding of the wider business issues that you may be able to relate to. They can also support you by sounding out other interested that parties need to be consulted and reassured.

Your credibility

Putting forward a case for investment or change is always much easier if you have become known for promoting sensible and effective ideas for saving money, energy or carbon. This is one reason for portraying 'making a business case' as a continuous process rather than a discrete event. Ultimately, senior management should be asking you for ideas, rather than you having to pitch to them.

Strategically it is sensible to pick some "easy winners" which give good savings for little investment or effort. The next step is to publicise the success, quantifying it as much as possible.

It will take time to build a reputation, but just one failure can set your reputation back a long way, so always follow these rules:

- Evaluate projects diligently – be convinced before advocating them.
- Never make exaggerated claims.
- Try to leave yourself headroom to deliver more than you promised.

- When you get approval for something, implement it without delay and do everything you can to ensure its success.
- Keep up with the news – become an authority on the subject.
- Make sure people know what you have achieved, and keep it all on record.

11 Energy Management Systems

Energy management is a culture for continual improvement of energy performance and efficiency that's integrated within an organization's normal business practice. It positions an organization to achieve energy and cost savings through informed decision making and the implementation of energy saving practices for facilities, processes, equipment and operations [39].

A successful **ongoing** programme of identifying and implementing successful motor energy saving opportunities relies on an organisation having proper systems in place.

Without these systems, there will be no framework for management to easily approve investments, or for implementing and reviewing their actual performance.

If the systems are incomplete or weak, you need to identify these problems and take action as far as you can to ensure that your measures don't fail because of these systemic problems.

If you are in a position to influence the development of a formal energy management system (EnMS), then consider attending a formal course on this.

The benefits of energy management include:

- Improved profits
- Reduced energy costs
- Improved processes
- Reduced emissions
- Reduced risk to energy price fluctuations

Additional benefits of Energy Management:

- Might help management meet legal obligations
- Green credentials can give competitive advantage
- Improved working conditions and productivity

Energy Management is not a single project, it is an ongoing programme and way of doing things.

The growing importance of improving energy performance in industry has led to the development of a standard for the implementation of Energy Management Systems (ISO 50001:2011, Energy management systems – Requirements with guidance for use [40]).

ISO 50001:2011 offers a framework for organizations to [41]:

- Establish an energy policy;
- Allocate resources and create teams to effectively implement an energy management system;
- Conduct energy reviews;
- Identify opportunities for improving energy performance;
- Establish baselines and energy performance indicators for tracking progress;
- Set energy performance improvement targets; and
- Implement action plans to achieve those targets.

ISO 50001 is based on the ISO management system model familiar to more than a million organizations worldwide who implement standards such as ISO 9001 (quality management), ISO 14001 (environmental management), ISO 22000 (food safety), ISO/IEC 27001 (information security). In particular, ISO 50001 follows the Plan-Do-Check-Act process for continual improvement of the energy management system.

The approach can be briefly described as follows.

► Plan : conduct the energy review and establish the baseline, energy performance indicators (EnPIs), objectives, targets and action plans necessary to deliver results in accordance with opportunities to improve energy performance and the organization's energy policy.

► Do : implement the energy management action plans.

► Check : monitor and measure processes and the key characteristics of its operations that determine energy performance against the energy policy and objectives and report the results.

► Act: take actions to continually improve energy performance and the EnMS.

And is summarised on the following process chart, from ISO 50001:

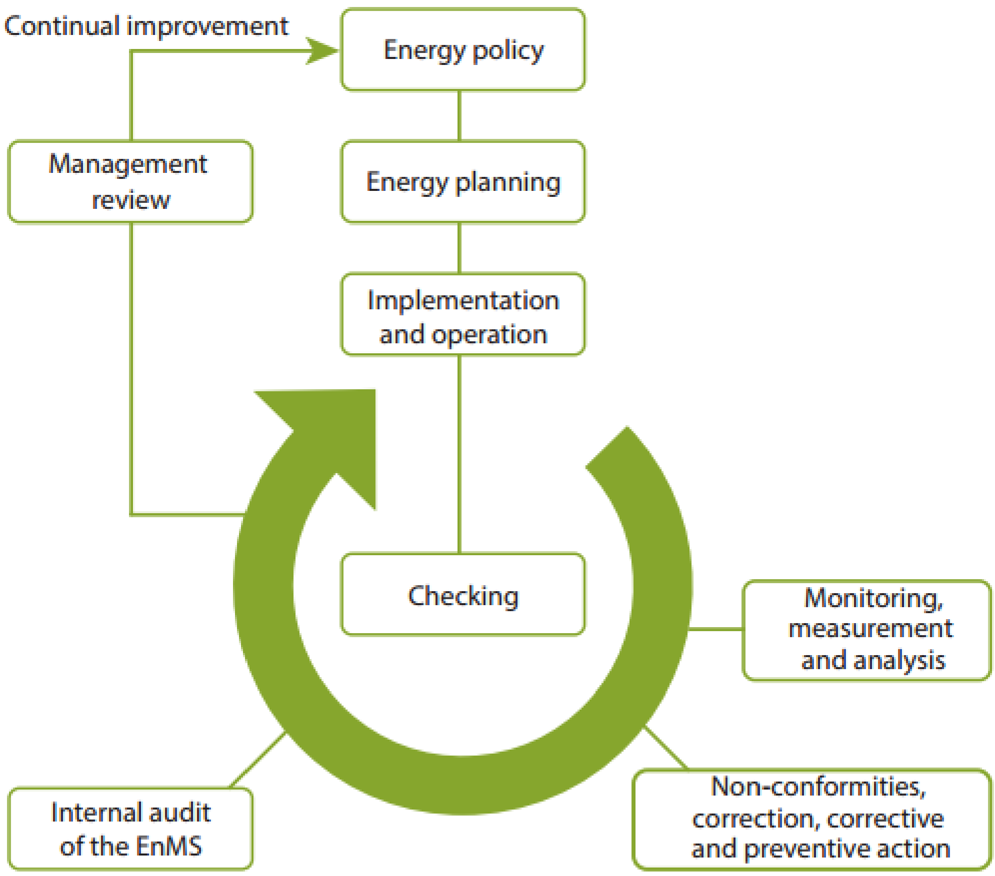


Figure 75 EnMS model for ISO 50001

Within energy management, according to ISO 50001, the following points are particularly relevant for motor systems. Motor systems aspects can easily be integrated and are already discussed in this manual (maintenance, motor selection, VSD). In fact, motor systems constitute a logical starting point for initiating an energy management program as it includes:

- Establishing and **setting criteria for the effective operation and maintenance** of significant energy uses, where their absence could lead to a significant deviation from effective energy performance.
- The organization shall **consider energy performance improvement opportunities and operational control in the design of new, modified and renovated facilities, equipment, systems and processes** that can have a significant impact on its energy performance.
- The organization shall establish and implement the **criteria for assessing energy use, consumption and efficiency over the planned or expected operating lifetime when procuring energy using products, equipment** and services which are expected to have a significant impact on the organization's energy performance.
- The organization shall define and **document energy purchasing specifications**, as applicable, for effective energy use.
- **Maintaining records of corrective actions** and preventive actions.

12 Further Reading

12.1 Text Books

- *Energy-Efficient Motor Systems – A Handbook on Technology, Programs, and Policy Opportunities*, Steve Nadel, Michael Shepard, Steve Greenberg, Gail Katz, Anibal T. de Almeida, ACEEE
- *Energy Efficiency Improvements in Electric Motors and Drives*, Anibal T. de Almeida, Paolo Bertoldi, Hugh Falkner (Editors), Springer, 2000.
- *Electric Motors and Drives – Fundamentals, Types and Applications*, Austin Hughes, BH Newnes, 4nd Edition, 2013
  The Control Techniques Drives and Controls Handbook, Bill Drury, The Institution of Engineering and Technology, 2nd Edition, 2009

12.2 Standards

Performance rating of motors

- IEC 60034-1: Rotating electrical machines – Part 1: Rating and performance
- *IEC 60034-2-1 (Ed. 2.0): Rotating electrical machines – Part 2-1:Standard methods for determining losses and efficiency from tests (excluding machines for traction vehicles), 2014*, which describes methods to determine motor efficiency from tests.
- IEC 60034-2-2: Rotating electrical machines - Part 2-2: Specific methods for determining separate losses of large machines from tests - Supplement to IEC 60034-2-1
- IEC/TS 60034-2-3:2013, Specific test methods for determining losses and efficiency of converter-fed AC induction motors
- IEC 60034-4: Rotating electrical machines – Part 4: Methods for determining synchronous machine quantities from tests
- IEC 60034-19: Rotating electrical machines – Part 19: Specific test methods for d.c. machines on conventional and rectifier-fed supplies
- IEC TS 60034 – 25 (Ed. 2): Rotating electrical machines - Part 25: Guidance for the design and performance of a.c. motors specifically designed for converter supply, 2007
- *IEC 60034-30-1 (Ed.1.0): Rotating electrical machines – Part 30-1: Efficiency classes of line operated AC motors (IE code), 2014*, which defines energy classes for electric motors rated for operation on a sinusoidal voltage supply.
- IEC/TS 60034-30-2:2016, Efficiency classes of variable speed AC motors (IE-code)
- IEC 61800-2: Adjustable speed electrical power drive systems - Part 2: General requirements rating specifications for low voltage adjustable frequency a.c. power drive systems.

- IEC 61800-9-1:2017, Adjustable speed electrical power drive systems - Part 9-1: Ecodesign for power drive systems, motor starters, power electronics and their driven applications - General requirements for setting energy efficiency standards for power driven equipment using the extended product approach (EPA) and semi analytic model (SAM).
- IEC 61800-9-2:2017, Adjustable speed electrical power drive systems - Part 9-2: Ecodesign for power drive systems, motor starters, power electronics and their driven applications - Energy efficiency indicators for power drive systems and motor starters.
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Selection and application of motors

- *IEC 60034-31 (Ed.1.0): Rotating electrical machines - Part 31: Selection of energy-efficient motors including variable speed applications - Application guide, 2010*
- IEC 60072-1: Dimensions and output series for rotating electrical machines - Part 1: Frame numbers 56 to 400 and flange numbers 55 to 1080
- IEC TS 60034-17: Rotating electrical machines — Part 17: Cage induction motors when fed from converters - Application guide
- NEMA MG10, Energy Management Guide For Selection and Use of Fixed Frequency Medium AC Squirrel-Cage Polyphase Induction Motors
- NEMA MG11, Energy Management Guide For Selection and Use of Single-Phase Motors

12.3 Other Useful Documents

- *Continuous Energy Improvement in Motor Driven Systems- A Guidebook for Industry*, DOE/EERE/Industrial Technologies Program, 2014

- *Premium Efficiency Motor Selection And Application Guide- A Handbook for Industry*, DOE/EERE/Industrial Technologies Program, 2014

- *Improving Motor and Drive System Performance - A Sourcebook for Industry*, DOE/EERE/Industrial Technologies Program, 2008

- *Energy- efficient motor systems assessment guide*, CIPEC

- *Energy Efficiency Reference Guide Electric Motors,* NRCAN

- *Energy Management for Motor Driven Systems,* USDOE

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