TOPMOTORS FACT SHEET No. 32

Optimizing electric motor-driven systems

The five most important points

- Costs for electrical energy dominate the life cycle costs of an electric motor-driven system (EMDS), usually accounting for over 90%.
- Correctly rated (not oversized) electric motor-driven systems reduce the investment and operating costs.
- Requirements specification: to avoid oversizing, carefully define the requirements imposed by the process upon the drive.
- Optimize overall efficiency: all components of an electric motor-driven system must be matched to each other and designed for the (production) process in question. The efficiency of an electric motor-driven system depends in particular on the actual operating point.
- Involve specialists: where the required expertise in energy-efficient electric motor-driven systems is not available in-house, external specialists must be called in.

Introduction

Of the electrical energy consumed in Switzerland, industrial motors account for around 27% and electric motor-driven systems altogether for around 50%, as shown in Figure 1.

The number of electric motors installed in Switzerland was estimated in 2006 at 2.2 million (Baumgartner, 2006). More recent figures are not available.

A study of over 4 100 motors conducted in 2014 as part of the «EASY» financial incentives programme revealed the following:

- 56.4% of the motors surveyed had already exceeded their technical service life (< 1 kW: 10 years; 1 to 10 kW: 12 years, 10 to 100 kW: 15 years, > 100 kW: 20 years). The motors that had already exceeded their assumed technical service life had done so on average by 99%.

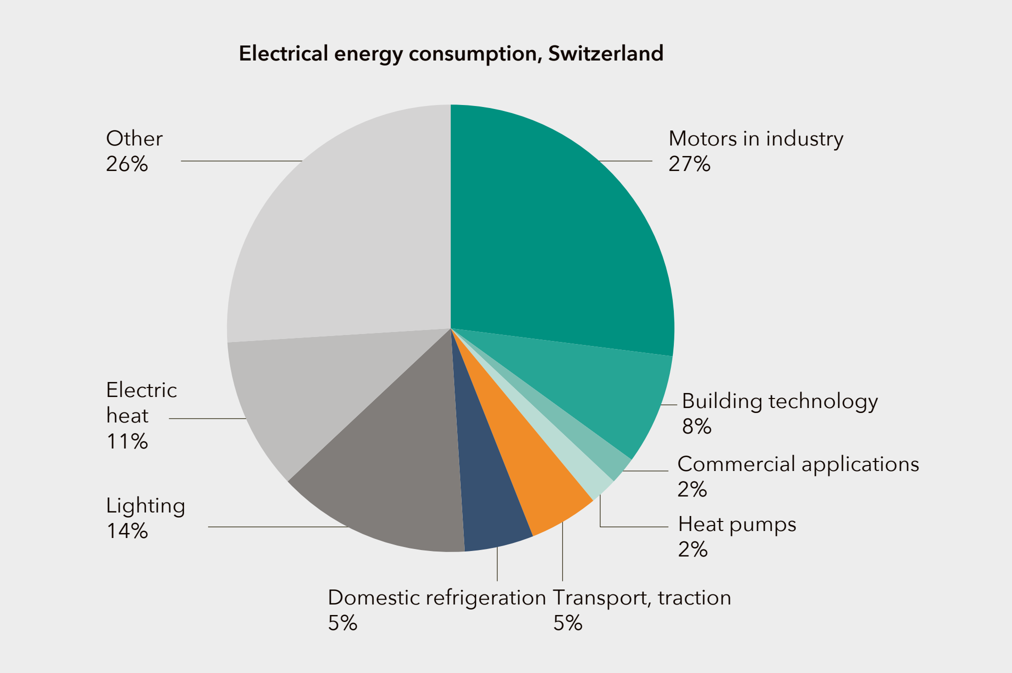

Figure 1: Share of electric motor-driven systems in Swiss electricity consumption (S.A.F.E./J.Nipkow, 2013). Electric motor-driven systems come under the categories of industrial applications, building technology, service sector applications, heat pumps, traction, transport and household appliances, which taken together account for 49% of consumption.

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▮ 19.8% of the motors surveyed were equipped with a variable frequency drive (VFD).

▮ 68% of the motors surveyed had an average load factor below 60% and are therefore considered oversized.

▮ Motors accounted for 86.8% of the electrical energy consumed by the industrial companies surveyed.

▮ Furthermore, studies by Topmotors often reveal potential energy savings for electric motor-driven systems of 20% to 30%, depending on the status quo.

Figure 2 shows the components of an electric motor-driven system. The system primarily comprises four components, namely the variable frequency drive, electric motor, mechanical components (e.g. V-belt) and application (e.g. fan). Electric motor-driven systems still present considerable potential for energy savings. Examples of estimated potential savings are 5% to 15% by resizing, 5% to 50% by process optimization, and 2% to 20% by the use of high-performance mechanical components (e.g. belts, gears, chokes, etc.) and modifications to the application (e.g. pumps, fans, compressors, transport) (figures: SFOE, Motor Summit 2021). The energy saving potential can be realized by two approaches:

1. Minimum requirements: Minimum energy efficiency requirements prevent components (such as motors and fans) with low energy efficiency from being used. Owing to the long technical service life of electric motors (between 10 and 20 years, depending on the motor's power rating), which is often also exceeded in practice, the minimum requirements are of great importance for electric motor-driven systems.

2. Replacement of existing electric motor-driven systems: This is significantly more difficult to accomplish. Investments in the energy efficiency of electric motor-driven systems are evidently often not made, even though their payback times would make them economically viable.

The following are common obstacles:

▮ The focus at purchase lies upon low purchase costs for a system; the operating costs over its service life are rarely taken into account.

▮ Expertise in the field of electric motor-driven systems is often lacking, particularly in SMEs.

▮ Production downtimes have a major impact on day-to-day business and often have costly and far-reaching consequences. Avoidable downtimes are therefore undesirable («never touch a running system»).

▮ Changes to certified processes are very difficult to implement and must be documented in detail.

▮ Trade secrets make it difficult for external specialists to analyse production data and measurement results.

The minimum requirements and legal provisions are universally binding and are now geared to improving energy efficiency at the component level. However, since interaction between the individual components in the electric motor-driven system is complex and they are tuned to the process without reference to minimum energy efficiency requirements, the current specifications cannot guarantee optimum overall efficiency at the system level. When legacy installations are replaced, operators can influence the energy consumption and operating costs of their electric motor-driven systems directly, substantially and in the long term. It is therefore particularly important that the EMDS as a whole and the various potential savings always be considered on a case-by-case basis.

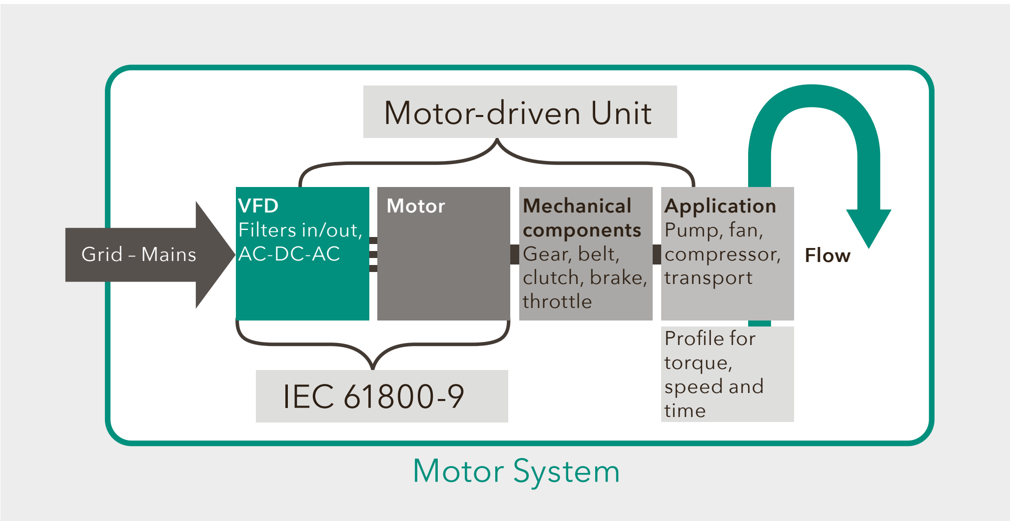


Figure 2: Definition of an electric motor-driven system. (Source: Topmotors)

Current minimum requirements

The www.topmotors.ch/normen website provides detailed information on standards and regulations governing electric motor-driven systems. These are summarized below:

Electric motors and variable frequency drives

As of **1 July 2021**, the following applies to commercial sale and placing on the market:

- **Efficiency class IE2 (or higher) for motors** with a rated power from 0.12 kW and below 0.75 kW
- **Efficiency class IE3 (or higher) for motors** with a rated power from 0.75 kW up to 1 000 kW
- **Efficiency class IE2 for variable frequency drives** designed for operation with motors from 0.12 kW to 1 000 kW

In addition, as of **1 July 2023**, motors with a rated power of at least 75 kW but no more than 200 kW placed on the market and sold commercially must satisfy the requirements of efficiency class IE4 (or higher). See:

- Swiss Energy Efficiency Ordinance (EnEV) Annex 2.7 (Requirements for energy efficiency and for placing on the market and commercial sale of motors and variable frequency drives) Download (EnEV, 2017)
- This information concerning the regulations in force in Switzerland and the EU can also be found in compact form in Topmotors INFO No. 1 (available in German, French and Italian).
- Further information on exceptions, transition periods and sale of residual stocks of IE1, IE2 and IE3 motors which do not satisfy the applicable regulations: Topmotors INFO No. 2 (available in German, French and Italian).

Circulators

As of 1 August 2015, glandless pumps (circulators) with a hydraulic power of 1 W to 2,500 W must have an energy efficiency index (EEI) of 0.23.
See EnEV Annex 2.8 (Requirements for energy efficiency and for placing on the market and commercial sale of glandless circulators) Download (EnEV, 2017)

Water pumps

As of 1 January 2015, water pumps operating at optimum capacity must comply with the required hydraulic efficiency, with a minimum efficiency index (MEI) of 0.4.
See Annex 2.9 (Requirements for energy efficiency and for placing on the market and commercial sale of water pumps) Download (EnEV, 2017)

Fans

As of 1 January 2015, fans with an electric power of between 125 W and 500 kW must satisfy the minimum energy efficiency requirements of the second phase.
See EnEV Annex 2.6 (Requirements for energy efficiency and for placing on the market and commercial sale of fans) Download (EnEV, 2017)

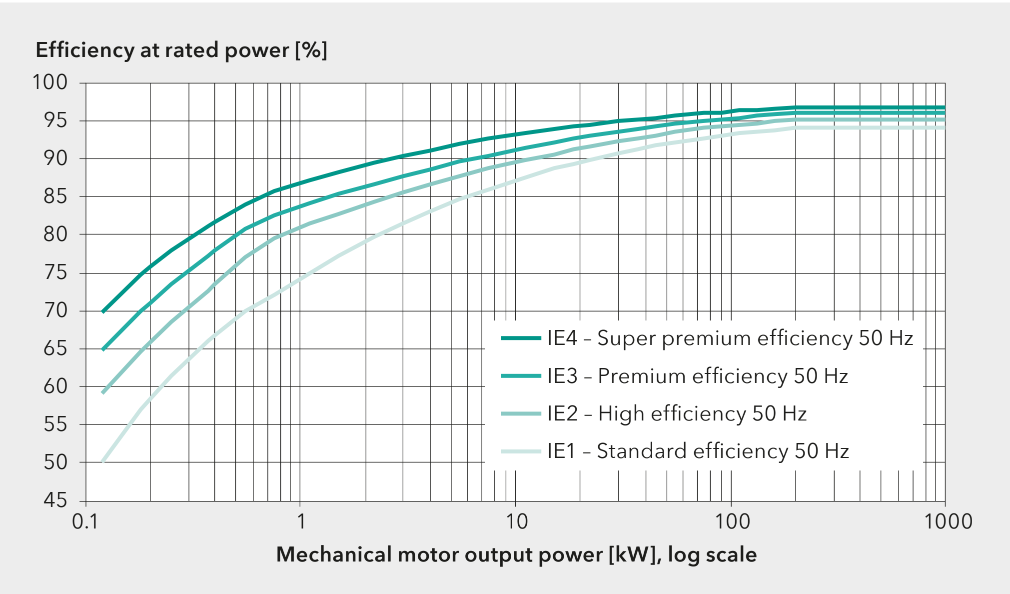


Figure 3: Efficiencies of 4-pole electric motors according to IEC 60034-30-1:2014.

Energy efficiency classes for motors, variable frequency drives and motor-driven systems

With the aim of reducing the power consumption of electric drives, regulations have been adopted in Switzerland governing the minimum energy efficiency to be achieved by electric motors and variable frequency drives (as of July 2021). For this purpose, electric motors and variable frequency drives (VFDs) are assigned to efficiency classes according to their losses, i.e. their energy conversion efficiency. The efficiency classes are defined by international standards of the International Electrotechnical Commission (IEC); they therefore reflect a worldwide consensus and are referred to by the International Efficiency code (IE code) or International Efficiency System code (IES code).

IE efficiency classes for motors

Electric motors are assigned to classes according to their efficiency. A distinction is drawn between line-operated constant-speed motors and those operated at variable speeds only in conjunction with variable frequency drives.

Line-operated constant-speed motors

IEC 60034-30-1:2014 defines four efficiency classes (see Table 2). The reference value for the minimum efficiency to be attained in the efficiency class concerned depends on a range of factors, including:

- The rated (mechanical) power of the motor: 0.12 to 1 000 kW
- The number of poles of the motor: 2 to 8-pole motors

Annex A of the standard outlines a prospective IE5 efficiency class. It is anticipated that motors in this class will have losses approximately 20% lower than those of IE4 motors. However, class IE5 is not effectively defined, and no minimum efficiency regulations exist in Switzerland that refer to it (as at December 2021).

Variable speed motors (driven only by VFDs)

The IEC TS 60034-30-2:2016 technical specification for variable speed electric motors driven only by variable frequency drives has been published. According to this technical specification, variable speed motors suitable for continuous operation can also be assigned to the five classes IE1, IE2, IE3, IE4, IE5 according to their energy efficiency.

IE code for variable frequency drives

As of 1 July 2021, minimum efficiency requirements also exist for variable frequency drives designed for driving motors with a rated power of 0.12 to 1 000 kW. Accordingly, variable frequency drives must satisfy at least the requirements of energy efficiency class IE2, see EnEV Annex 2.7. Variable frequency drives are assigned to international efficiency classes IE0, IE1 and IE2 in accordance with IEC 61800-9-2:2017, see Table 1. The VFDs are assigned to the three efficiency classes by comparing of their power loss with that of a reference VFD representing current best practice, see Figure 4.

IE code	Efficiency class
IE4	Super premium efficiency
IE3	Premium efficiency
IE2	High efficiency (formerly Eff1)
IE1	Standard efficiency (formerly Eff2)

Table 2: IE code for efficiency classes according to IEC 60034-30-1:2014.

Scope		Code	Efficiency classes	Standard or technical specification (TS)
Motor	Constant-speed motor, line operation	IE code	IE1, IE2, IE3, IE4	IEC 60034-30-1:2014
Motor	Variable-speed motor, intended for operation with variable frequency drive, not directly line operated	IE code	IE1, IE2, IE3, IE4, IE5	IEC TS 60034-30-2:2016
CDM	Variable frequency drive	IE code	IE0, IE1, IE2	IEC 61800-9-2:2017
EMDS	Electric motor-driven systems (includes motor and CDM)	IES code	IES0, IES1, IES2	IEC 61800-9-2:2017
EPA	Extended product approach	–	–	EN 50598-3:2015

Table 1: IE code and IES code for the classification of electric motors or variable frequency drives and electric motor-driven systems.

IES code for electric motor-driven systems

An electric motor-driven system, e.g. in a ventilation system in continuous operation, may give rise to considerable annual energy costs. Energy costs can be kept low in the long term by means of an energy-efficient electric motor-driven system. In Switzerland, the requirements are currently specified for individual components, i.e. motors, variable frequency drives, pumps or fans, by the Swiss Energy Efficiency Ordinance (EnEV). Effective interplay between all the components, and thus also the system efficiency which ultimately determines the electricity costs, is however frequently neglected during planning. This is often because the planning process involves multiple parties each performing discrete tasks, and because additional minimum requirements for the energy efficiency of the electric motor-driven system as a whole may not have been set out by the client. One of the next steps is for these requirements to be formulated with respect to multiple components. This forms part of the extended product approach (see Figure 6). Table 1 lists international standards referred to for this purpose.

Electric motor-driven systems are assigned to the three IES efficiency classes by comparing the power loss of the system with that of a reference drive system (see Figure 5). The scope of the IES efficiency classes includes the 0.12 kW – 1 000 kW power range, the 100 V – 1 000 V voltage range and single-axis AC/AC electric motor-driven systems.

The system approach enables the efficiency (class) of an entire electric motor-driven system to be determined, taking account of interaction between the individual components. This in turn enables cost-effectiveness to be calculated more precisely and the electric motor-driven system to be dimensioned more accurately. The IES efficiency classes are an important step towards designing dynamic processes and exploiting valuable energy efficiently. A timetable for the introduction of regulations governing the energy efficiency of electric motor-driven systems (EMDSs) is not yet available.

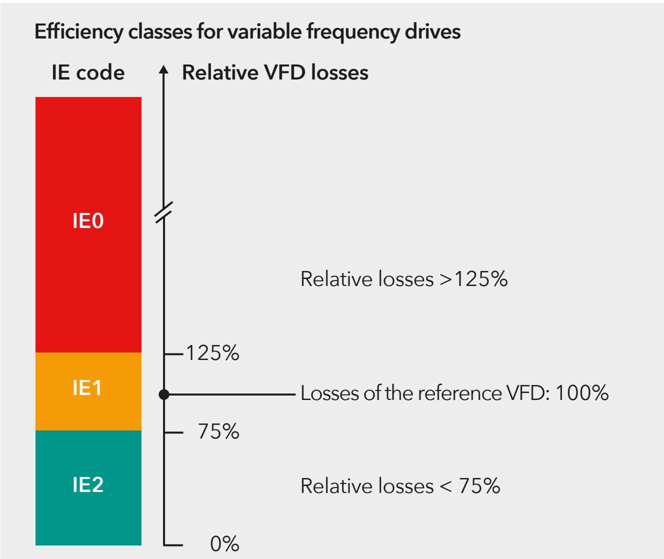


Figure 4: Efficiency classes for variable frequency drives according to IEC 61800-9-2:2017. The energy efficiency of a variable frequency drive is assessed by comparison. The values for power loss stated in the standard serve as the reference.

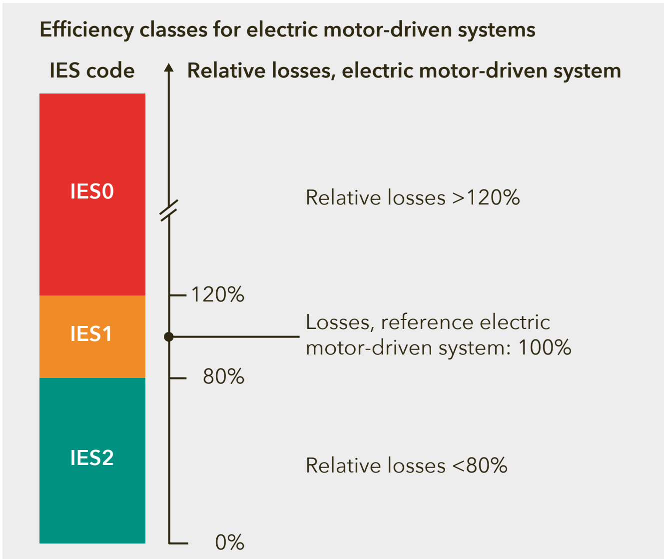


Figure 5: IES efficiency classes for electric motor-driven systems (EMDSs) according to IEC 61800-9-2:2017. The energy efficiency of an electric motor-driven system is assessed by comparison. The values for power loss stated in the standard serve as the reference.

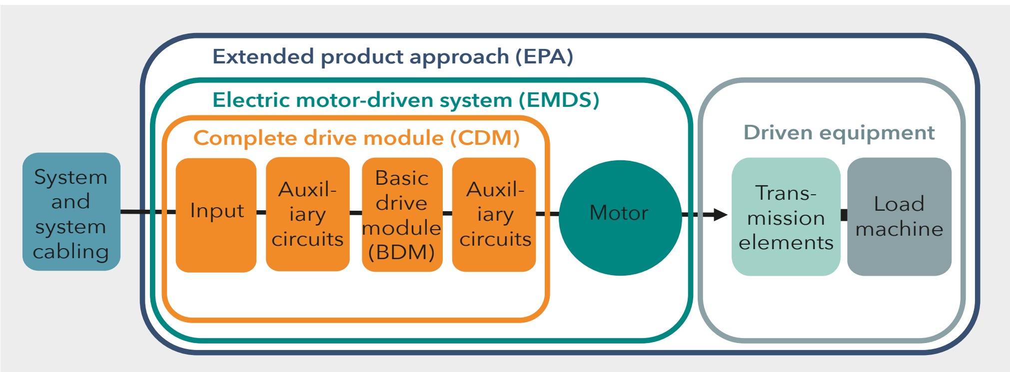


Figure 6: Extended product approach (Source: Topmotors)

Systematic optimization of electric motor-driven systems

An electric motor-driven system is able to function efficiently only if all components are matched to each other and are operated at their optimum operating point. In addition, it must be determined whether components such as a transmission (e.g. a belt) are necessary for the application, or can be omitted. This enables costs of purchase and upkeep to be eliminated, and energy costs to be reduced owing to the improved energy conversion efficiency.

The decisive factor for the sizing of all components is always the process. It is therefore essential to analyse the process beforehand in the greatest possible detail. What pressure do I need for my process? What volume flow rate is required? Is it subject to fluctuations? Is a variable frequency drive for speed control necessary and beneficial?

Energy efficiency optimization should generally address the following aspects:

1. Do not oversize: design the system for the demand and critically review safety margins.
2. Operate the system only when required. Avoid operation with no benefit, e.g. at night.
3. Avoid standby losses.
4. If possible, drive the load directly rather than through a transmission (V-belt, gearbox, etc.).
5. Where advantageous, always use a variable frequency drive for power control.
6. Use high-efficiency components:
   - Motors: IE4 or higher
   - Variable frequency drives: IE2 or higher (all VFDs with relative losses <75% are classified as IE2. Critical consideration of the VFD›s relative losses is therefore advisable).
   - Best available technology for pumps, fans, VFDs, etc.

Efficiency and efficiency chains

The primary concern for electric motor-driven systems employed in an industrial environment is their costs. From an economic perspective, the cost-benefit ratio is important. From a technical perspective, the aim is to exploit electrical energy as effectively as possible. The electric motor is an energy converter: it converts electrical energy into a form of energy that can be exploited mechanically. The efficiency (specifically the energy conversion efficiency) of the motor describes how much energy is lost during this conversion process. In physical terms, the ratio of the mechanical power output to the electrical power input is considered:

$$\eta = \frac{P_{out}}{P_{in}} = \frac{P_{out}}{P_{out} + P_{loss}} = \frac{P_{in} - P_{loss}}{P_{in}}$$

Efficiency	η	1
Power output	P_{out}	W
Power input	P_{in}	W
Power loss	P_{loss}	W

The efficiency is a ratio. For an electric motor, it lies between 0 and 1 and is usually expressed as a percentage (0 – 100%).

For an electric motor, a high efficiency means:

- $\eta \geq 93.3\%$ for an IE4 motor with a rated power of 11 kW (IEC 60034-30-1:2014).
- Owing to its favourable technical characteristics, the motor has a lower power loss than motors in a lower efficiency class.
- The motor gives rise to comparatively low operating costs, even in the partial load range.

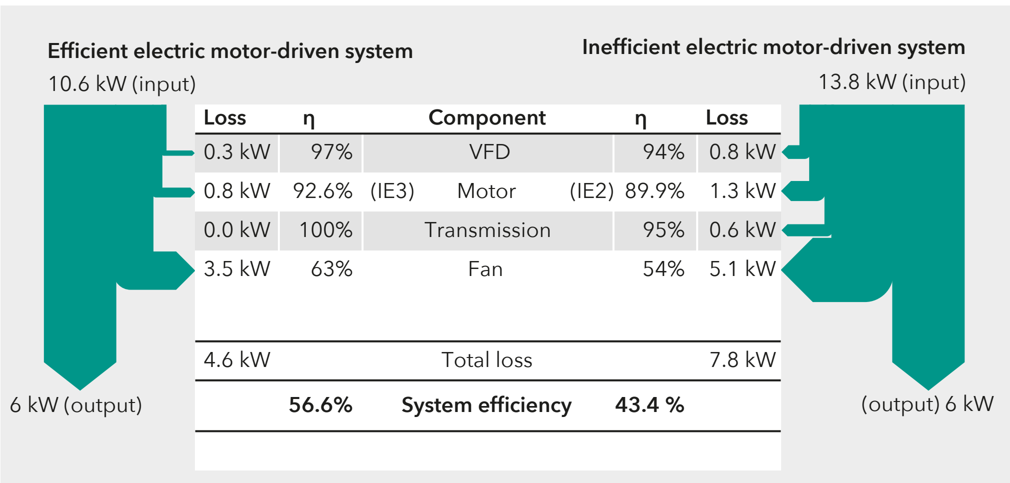
Example: overall efficiency of electric motor-driven systems

Figure 7 shows, for two different electric motor-driven systems, the power flow and the losses arising through to the load power of the application. The two electric motor-driven systems both deliver 6 kW of power to the process, but differ significantly in the energy they require. The higher energy conversion efficiencies in the more efficient electric motor-driven system lead to a reduction in the required (input) electrical power of 3.2 kW (−24%). Over one year, this results in savings of CHF 2 185 (4 500 operating hours/year, electricity price: CHF 0.15/kWh). Often, most of the losses occur in the components upstream and downstream of the electric motor. In the interests of high overall energy efficiency of the electric motor-driven system, it is therefore important for each component in the power flow to contribute as little as possible to the losses of the system as a whole. Efficient components such as IE4 motors constitute the ideal starting-point for an electric motor-driven system with high overall energy conversion efficiency. To calculate the total efficiency η_{total} of the electric motor-driven system, the efficiencies of the individual components must be multiplied together. For a system consisting of a variable frequency drive (97%), motor (92.6%), transmission (100%) and fan (63%), the overall efficiency is only 56.6%:

$$\eta_{total} = \eta_{VFD} \times \eta_{motor} \times \eta_{transmission} \times \eta_{fan}$$

$$= 0.97 \times 0.926 \times 1.0 \times 0.63 = 0.566 = 56.6\%$$

Although some of the individual components exhibit a relatively high efficiency, the system efficiency is 43.4% (inefficient electric motor-driven system) and 56.6% (efficient electric motor-driven system). Consequently, less than



Loss	η		Component		η	Loss
0.3 kW	97%		VFD		94%	0.8 kW
0.8 kW	92.6%	(IE3)	Motor	(IE2)	89.9%	1.3 kW
0.0 kW	100%		Transmission		95%	0.6 kW
3.5 kW	63%		Fan		54%	5.1 kW
4.6 kW			Total loss			7.8 kW
	56.6%		System efficiency		43.4 %	

Figure 7: System structure and power flow for two electric motor-driven systems. With reference to the case of a fan with a power requirement of 6 kW, two examples are compared: an efficient system (left, with IE3 motor) and an inefficient system (right, with IE2 motor and transmission).

half of the electrical energy used by the inefficient electric motor-driven system – and paid for – actually reaches the process. It must also be considered that information on the efficiency of components generally refers to the efficiency at the nominal operating point. However, an operating point that is not ideal often impacts negatively on the efficiency of the component concerned, and in turn on the system efficiency.

Load factor

When a motor is running at partial load, its efficiency is generally lower. This effect is particularly pronounced on older motors. The load factor is the ratio of the effective power consumed by the motor to the rated power consumption. It is a time-dependent variable that tracks the power consumption of the motor. For analysis purposes, the load factor is averaged over the period of measurement, for example one month or one year. The average is calculated for the operating time; periods during which the motor is completely switched off are ignored.

Indicator for motor sizing

If the load factor for one year is well below 1 (e.g. 0.5), the motor was generally operated in the partial load range over the year. Where the variation in power is not intentional, this indicates that an oversized, unnecessarily powerful motor was installed.

Caution: operation under partial load

Partial load, i.e. operation at a lower mechanical power output and/or a lower torque, reduces the efficiency. Depending on the motor and efficiency class, the drop in efficiency may be considerable. This is an important reason why oversizing of motors and the components of an electric motor-driven system should be avoided (see p. 6: Systematic optimization of electric motor-driven systems).
With the increasing use of variable frequency drives, operation under partial load and the associated general reduction in efficiency is becoming more and more important in the design of electric motor-driven systems. For this reason, the IEC has published technical specification IEC TS 60034-31:2021 and, in particular, the associated calculation table (.xls file, available for purchase) for calculating the efficiency of standards-compliant motors and the associated variable frequency drives under partial load.
The Topmotors INFO No. 3 (available in German, French and Italian) information sheet describes calculation of the efficiency during operation under partial load in greater detail.

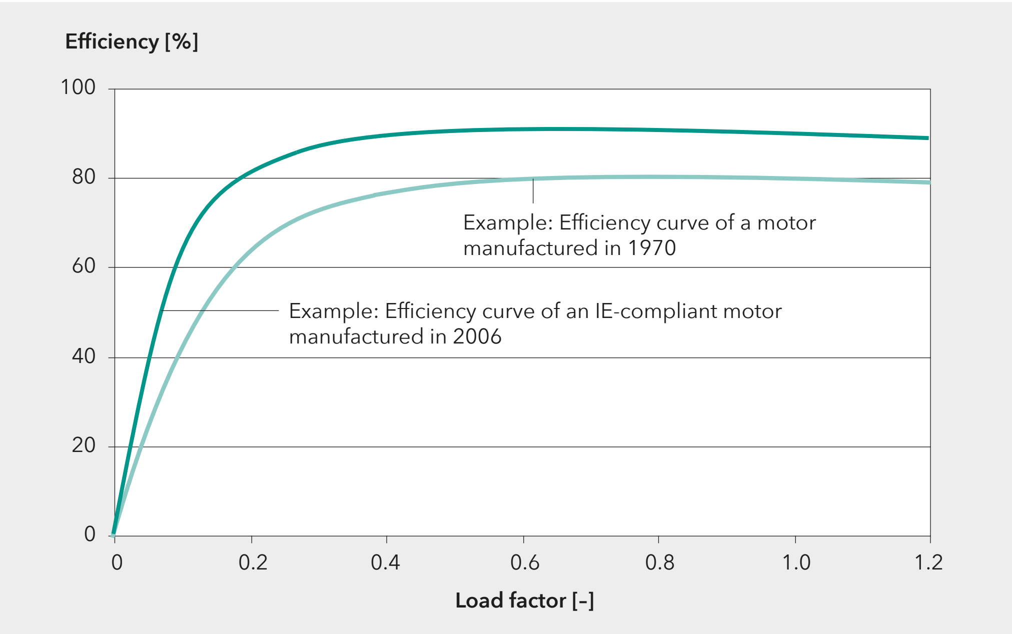


Figure 8: On older motors, not only is the nominal efficiency (for a motor of a given power) generally lower, the drop in efficiency as the partial load decreases is also more pronounced than on newer motors. (Source: Topmotors, 2014)

Measurements

For the optimization of existing electric motor-driven systems measurements provide important information on the mode of operation and power requirements. Electrical values (such as the electrical active power consumption) are relatively easy to measure and evaluate.
Conversely, measurement of mechanical values (volume flow rate, pressure, media velocities, rotational speeds, etc.) requires more complex equipment, particularly where hydraulic or pneumatic circuits must be opened for the purpose. Ultrasound can often be used for external measurement of the flow rate in pipes. Rotational speeds can often be determined without contact and are therefore easy to measure. Without use of a test bench, measurement of torques is highly resource-intensive, and is beneficial and necessary only in exceptional cases. A measurement specification must define what exactly is to be measured (and when and for how long), together with the benefit and objective of the measurement. Simple (electrical) measurements are often sufficient for an initial assessment, for example of the operating point of a pump or fan.

Step 1: Measurement concept

For each machine on which measurements are to be performed, the variable to be measured must be stated:

- Instantaneous power consumption
- Starting (power, current)
- Short-term behaviour (minutes, hours)
- Load profile, load factor, starting if applicable

The results can be used to determine the instantaneous load factor and, where operation is constant, to indicate a smaller motor size if appropriate. Where measurements are performed to determine the load factor for the purpose of sizing the motor, care must be taken to measure the maximum load case. Only where a higher power (for example for the manufacture of other products) is not required can a reliable statement be made regarding sizing, and a motor possibly downsized.
Clarity must first be obtained on the following points:

- Determine the advantageous/required duration of measurement.
- What resolution of the measurement data on the time axis (e.g. number of measurements per minute) is required? This allows the control solution to be reviewed and if applicable, use of a VFD to be recommended.
- Record the operating conditions of the installation during measurement (e.g. utilization, product, ambient temperature (season), etc.).
- What further variables must be measured in addition to the electrical power?
- Do variables exist that can be measured easily, or are secondary variables available such as operating hours, product, throughput, etc.? These would enable typical or maximum conditions for the year to be determined from the instantaneous measurement.

Operational constraints

Depending on the type of installation, individual machines or entire installations must be halted, shut down or operated with particular parameters during performance of the measurements. This often places constraints upon operation, and must be carefully coordinated. Access to the item under measurement (such as the motor or switchgear panel) must be clarified, and attention paid to safety aspects (electric shock, explosion protection, obstruction of escape routes). The measuring instruments must always be set up by in-house skilled personnel, with appropriate approval to connect them.

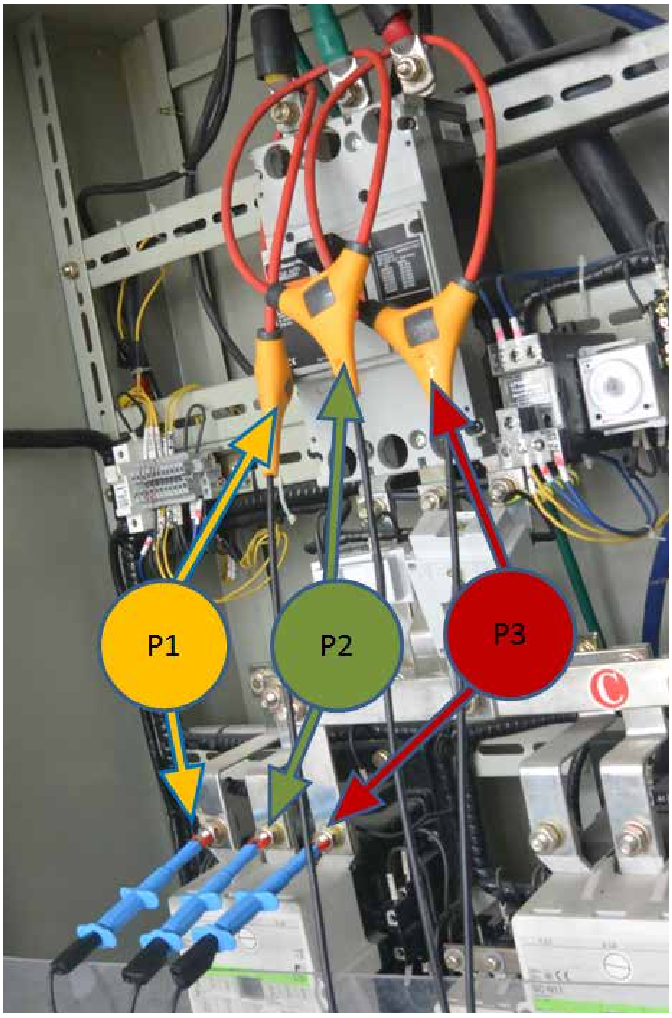


Figure 9: Example measurement installation (source: Topmotors)

Measuring equipment

Many industrial companies possess measuring equipment of their own for measuring the three-phase active power. This equipment includes current probes and often even data loggers to record the progress of processes over time. Current probes envelop the cable and enable the current to be measured without electrical connections having to be separated. Should the available measuring equipment be inadequate or more complex measurements and evaluations be planned, the company's motor servicing provider or motor supplier can be tasked with this work. For quick measurements for which high accuracy is not required, the power consumption can be determined with use of a single-phase power meter with current probes (a symmetrical three-phase supply is assumed here). In special cases, speed measurements can provide additional information on a motor's operating point.

Step 2: Performance of measurements

Preparation, assignment

To avoid disruptions to operation or measurement results that are incorrect or not meaningful, the procedure for measurement must be planned carefully, and the personnel involved must be informed. For the performance of complex series of measurements a measurement schedule may be advantageous.

Precise documentation of the measurement set-up and procedure, for example by means of photographs, is also important. An assignment should therefore be defined for each measurement project – irrespective of whether it is to be conducted internally or outsourced. The measurement assignment must specify the objective, the quantities to be measured, the accuracy, the boundary conditions and the form of reporting, as well as the costs and deadlines.

Precautions against electric shock

Only skilled personnel are permitted to manipulate live electrical equipment. Determining and ensuring the absence of voltage also requires skilled expertise. Errors in this area are the cause of most electrical accidents. Measurements must therefore be carried out by company electricians using equipment with which they are familiar.

Check connections and attachment of probes

Connections and probe positions must be checked carefully for each measurement. Reversed phases or current flow directions lead to problems of interpretation at later stages. Interpretation of pilot measurements is often valuable before a longer series of measurements is begun, and before the equipment is dismantled.

Step 3: Interpretation of results

Reporting

Based on the measurement data obtained, determine the desired results as set out in the objective/measurement concept. Document the calculation methods and steps. Summarize the results of the measurement project in a report, together with the measurement protocols.

Determining the load factor from power measurement

Since the power consumption during operation under rated conditions can be determined from the data sheet, the instantaneous load factor can be determined with a single measurement. The quotient of the electrical values yields the electrical partial load; to determine the mechanical partial load, the calculation must also consider the efficiencies. The power rating on the rating plate and data sheet of electric motors is the mechanical power P_{output} delivered by the motor at the shaft. The electric power consumed by the motor is denoted by P_{input}.

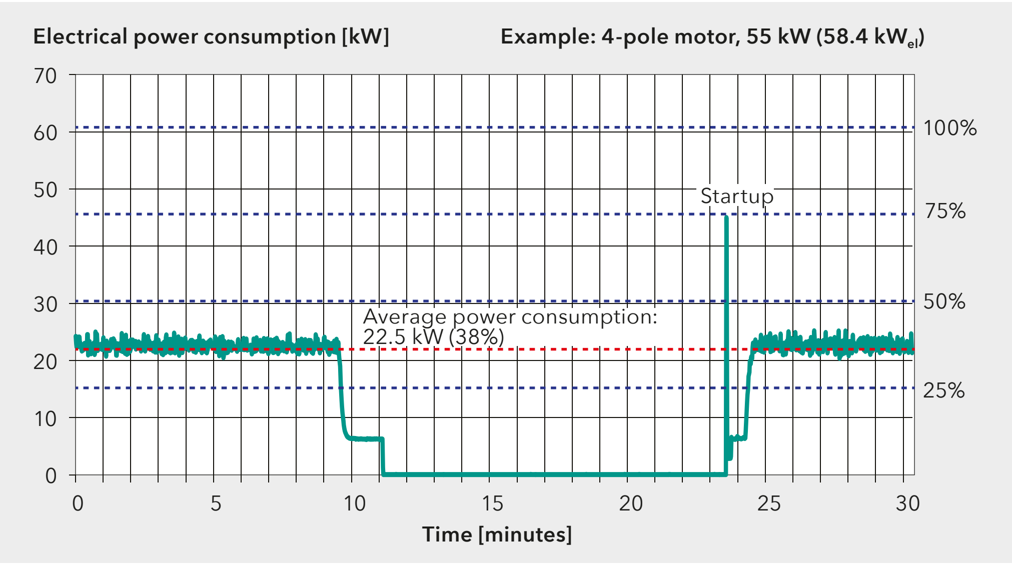


Figure 10: Example of a measurement diagram. The diagram shows the electrical power consumption with load fluctuations during operation, a pause, and starting of the motor. The very low average power consumption (38%) is conspicuous – a result of oversizing. (Source: Topmotors, 2014)

Smart metering

Measurement of the power consumption provides a good view of the use of motors at a given point in time. In the past however, this was generally a brief snapshot and often not suitable for optimizing an electric motor-driven system to maximum effect. Smart sensors and IoT solutions now enable electric motor-driven systems to be monitored continuously with little effort. The long-term data recorded by these solutions permit robust conclusions regarding resizing of the electric motor-driven system. Retrofitting of this technology is therefore worthwhile even on older motors scheduled for replacement in the coming years. In addition, continuous recording of operating parameters such as temperature, vibration and magnetization permits condition-based maintenance, which extends the service life of the electric motor-driven systems and reduces operating costs.

Variable frequency drives often provide interfaces permitting further use of performance data. They are therefore a suitable means of monitoring energy consumption continuously without the installation of additional sensors. Consequently, where a VFD is already installed, it may already be suitable for use for continuous recording of measurement data. Some VFDs also have power-saving functions. Activating these functions may enable operating costs to be reduced without further investment.

Procurement of motors; design and production of electric motor-driven systems

In the past, efficiency criteria were often not explicitly stated in invitations to tender for industrial plant and machinery. This placed declaration of the efficiency characteristics at the supplier's discretion, making comparison between several tenders virtually impossible. The following information can be used to specify differentiated efficiency properties in invitations to tender.

Standards

Table 1 lists the standards and efficiency classes that are of major relevance to electric motor-driven systems. These standards now enable suppliers of machines and systems to declare the efficiency of standards-compliant motors, variable frequency drives and electric motor-driven systems precisely by way of the efficiency class. For this reason, the highest efficiency class for each item should now be required of suppliers. Many variable frequency drives already exceed the requirements of today's highest efficiency class (IE2); detailed comparison of the relative losses of the VFD in different tenders is therefore advisable.

Planning of new installations

The planning and construction of completely new installations present the ideal conditions for considering the most efficient concepts and components. To ensure that efficiency objectives are given serious consideration by system planners and bidders, the following safeguards can be specified for (internal or external) orders:

- During conceptual planning and the selection of components for production plants, the total costs to be considered (total cost of ownership) are to include operation (energy) and maintenance over a service life of x years (e.g. 10).
- Calculation of the cost-effectiveness must take account of the significant increases in energy prices, for example with base values for 2021 and inflation rates for electricity.
- Should new, more efficient variants of technologies or components be available but not yet appear cost-effective a variant of the plan/tender employing them should be developed.

During the planning of new infrastructure systems or complete replacements, such as room heating, room ventilation/air conditioning, process water/cooling water/hot water supply systems, compressed air or transport systems, consideration must be given to the following particular aspects:

- Longer payback periods, e.g. 10 to 15 years, should generally be used for calculation of the cost-effectiveness of these installations than the periods used for production plants.
- Efficient control technologies employing speed control, i.e. variable frequency drives, must be used for all media delivery systems. Chokes and bypasses waste energy and should be avoided.

Life cycle cost

A complete life cycle cost analysis is useful for detailed comparison of variants. This analysis quantifies all investment and operational measures associated with a change. For a new installation, this means:

- Planning and purchase of the installation/components
- Installation and commissioning
- Operating costs (costs of energy, maintenance and upkeep, repairs) over the entire service life of 10 to 20 years (see Figure 11)
- Decommissioning and disposal

Where a legacy installation has not yet reached the end of its technical service life, its residual value is also taken into account.

Studies based on life cycle costs are not very common, since they consider a longer planning horizon.

Knowledge of the specific prices for motors and variable frequency drives and the overall efficiency of the electric motor-driven system at the operating point is essential for performance of a life cycle analysis. Precise (narrow) selection of the motor and variable frequency drive ratings reduces both investment costs and losses.

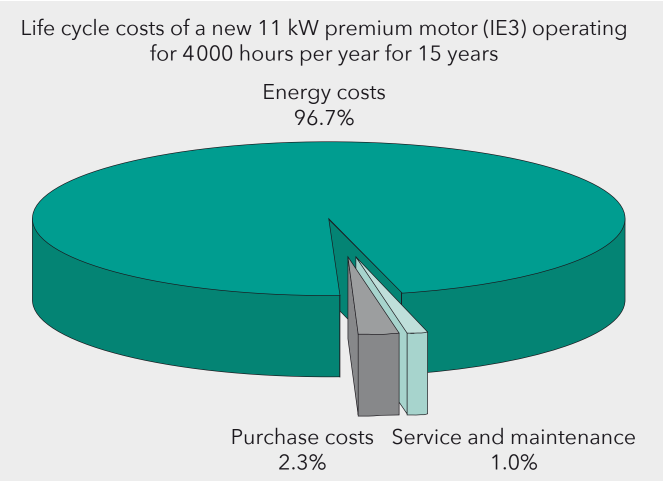


Figure 11: Example of the life cycle costs of a motor (Source: Topmotors)

Motor prices

Prices for motors fluctuate widely. It is common, for example for different discounts to be granted depending on the customer and the quantities ordered.The diagram shows motor prices in CHF/kW as a function of the rated power for IE2, IE3 and IE4 motors. There is virtually no further drop in actual prices in CHF/kW for motors above 10 kW. This means that precise (narrow) selection of the motor rating saves both investment costs and energy costs.

Additional costs for more efficient motors

To determine the anticipated additional costs of more efficient motors, the Topmotors Market Report analysed and evaluated the sales prices of motors in Switzerland. The purchase cost of an IE2 motor (100%) served as reference. The costs of a IE3 and IE4 motor were found to be 15% and around 33% respectively above those of a comparable IE2 motor.

Efficiency class	IE2	IE3	IE4
Relative price	100%	115%	133%

Table 3: Price comparison of efficiency classes of motors: average of specific prices for IE2, IE3, IE4, each from 0.12 kW up to 1 000 kW (Source: Topmotors Market Report, 2020)

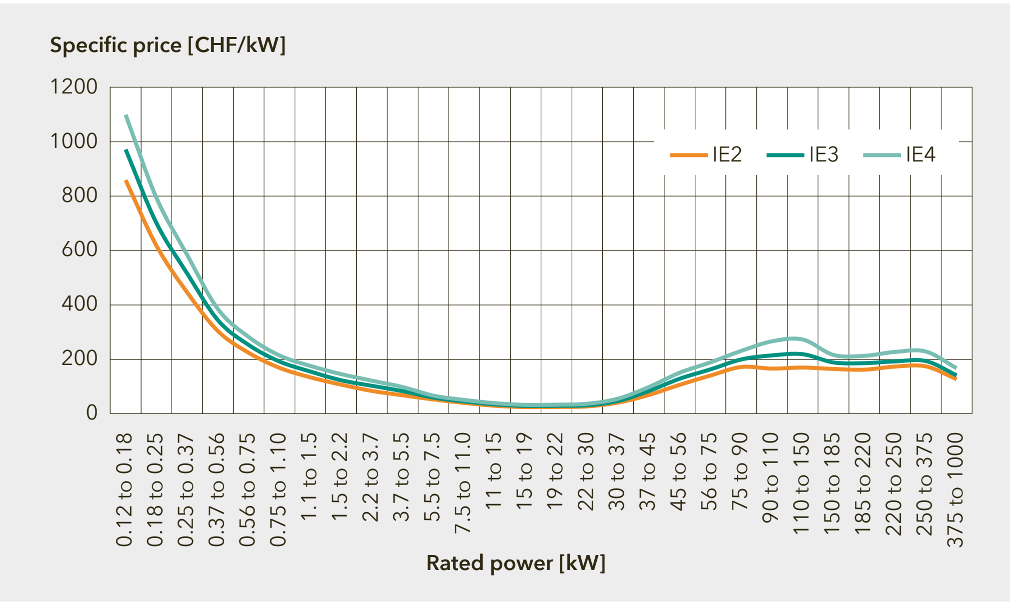


Figure 12: Specific motor price in CHF/kW, 2019. (Source: Topmotors Market Report 2020)

Package of measures

An important step is combining the individual measures under consideration to form a package of measures. For machines of the same design, the individual measures are ranked according to payback and energy savings (see Fig. 13). The cumulative payback and cumulative savings show clearly up to what point a number of measures form a good package for implementation.

Experience shows that below a critical threshold with a payback time of (for example) three years, around 80% of all measures studied can be implemented. Measures with a very short payback time (less than one year) are also seen to offset important measures with a payback time of five years or more.

Motor technologies

The various motor technologies are described in detail in Topmotors Fact Sheet No. 29. The fact sheet shows the advantages and disadvantages for example of asynchronous motors (ASMs, Figure 14), permanent magnet motors (PMMs, Figure 15) and synchronous reluctance motors (SRMs, Figure 16), compares them with each other and describes typical applications for each technology. A selection of important points is shown below.

The user must determine when the use of a high-efficiency motor with closed-loop control is advantageous and what motor technology is best suited to the application under consideration. The technologies differ and have advantages and disadvantages depending on the application. Differences include the following aspects:

- Efficiency at a range of speeds
- Efficiency at a range of torques
- Weight
- Suitability for frequent and rapid run-up
- Use with/without VFD (SRMs and PMMs require a VFD).

Figure 14: Schematic diagram of an asynchronous motor (ASM). (Source: Danfoss)

Figure 15: Two permanent magnet motors: above with embedded magnets, below with surface-mounted magnets. (Source: Danfoss)

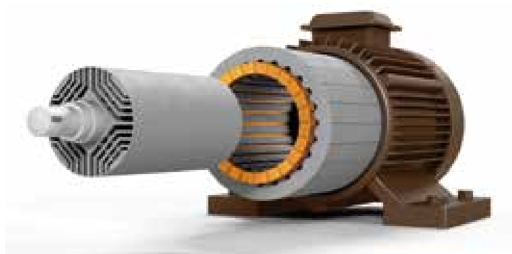


Figure 16: Schematic diagram of a synchronous reluctance motor (SRM). (Source: Danfoss)

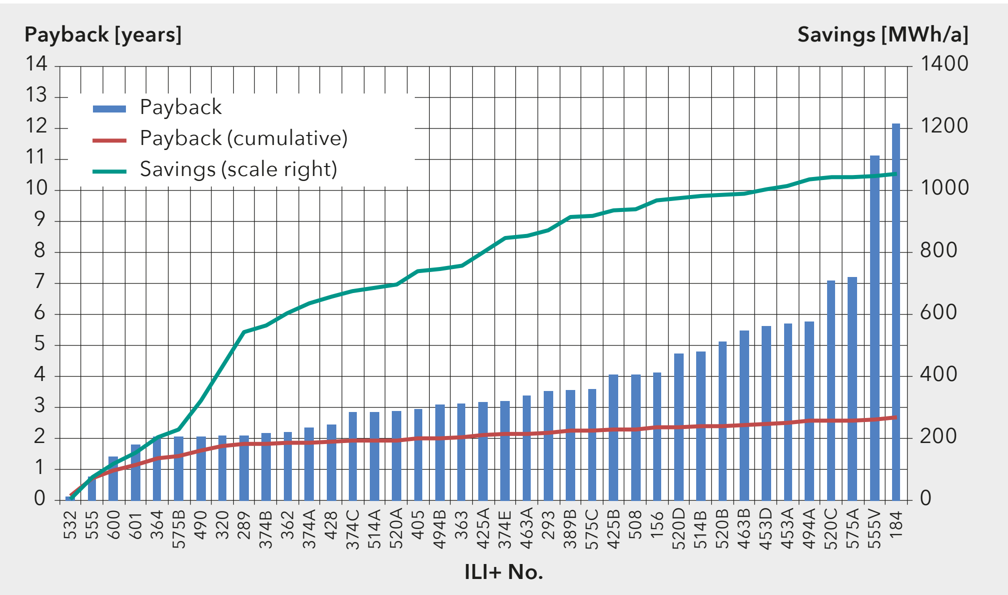


Figure 13: Example of a package of measures: individual measures, ranked by payback and contribution to the energy savings. Payback, total package: 2.4 years (cumulative). (Source: Topmotors, Easy financial incentives programme, 2014)

Advantages and disadvantages of modern high-efficiency motors

A higher motor efficiency makes a positive contribution to electrical energy savings. The extra costs that are often entailed are paid off by the reduced energy costs during operation. At above 2000 operating hours per year, the payback is usually within five years. In addition, correct sizing and operation geared to the load are always beneficial, and reduce the operating costs. Some motor technologies enable smaller and lighter motors to be used with the same power and higher efficiency. Lower losses and thus lower temperatures generally have a positive effect on the technical service life and operating costs.

Efficient motors run faster

The rated speed of ASMs and PMMs increases slightly with rising efficiency. This effect is due to the lower slip between the mains frequency and the rotor speed. When a legacy motor is replaced one-for-one with a new motor of the same rating (without use of a VFD), it must be taken into account that pumps and fans, for example, run at a slightly higher speed and thus deliver more air or water than previously. As a result, more electrical power may be consumed (cube law for the relationship between speed and power), despite the motor being more efficient. This effect can be avoided by adjusting the transmission (ratio) or by use of a VFD.

Variable frequency drives (VFDs)

What is a variable frequency drive?

A variable frequency drive (VFD) enables the speed of electric motors to be controlled. To achieve this, the VFD generates an AC voltage with variable frequency and amplitude from the AC line voltage (e.g. 400 V) and frequency (50 Hz) for supply to electric motors. This enables a closed-loop control system with sensors for pressure, temperature, etc. to be created that delivers the required power (and no more) at the right moment, for example in the form of the volume flow rate of a pump, fan, etc. This in turn delivers considerable energy savings compared to solutions used in the past employing chokes and valves.

Variable frequency drives are now indispensable in numerous small and larger applications, since they permit soft starting at high torque, smooth and stepless acceleration, and load-dependent control in the interests of lower electrical energy consumption. Furthermore, a VFD can serve as an interface for integrating electric motor-driven systems into IoT applications.

Savings potential of variable frequency drives in closed-circuit applications

For quadratic torque applications such as closed-circuit pumps, air delivery systems, etc., variable frequency drives have high potential efficiency: even a small percentage reduction in the volume flow rate yields relatively high energy savings compared to mechanical throttling, as shown in Figure 17 for a circulator.

The losses of the variable frequency drive are also shown schematically in Figure 17. Owing to the intrinsic losses of the VFD (4% in this example), the power consumption of the variable speed drive employing a VFD is greater (P = 104%) at the rated load (Q = 100%) than when the motor is operated on-line without a VFD (Q = 100%, P = 100%).

A survey by Topmotors of 4142 motors in use in Swiss industry showed that around 50% of all electric motor-driven systems would be suitable for equipping with VFDs, but that only around 20% were so equipped (as at 2013).

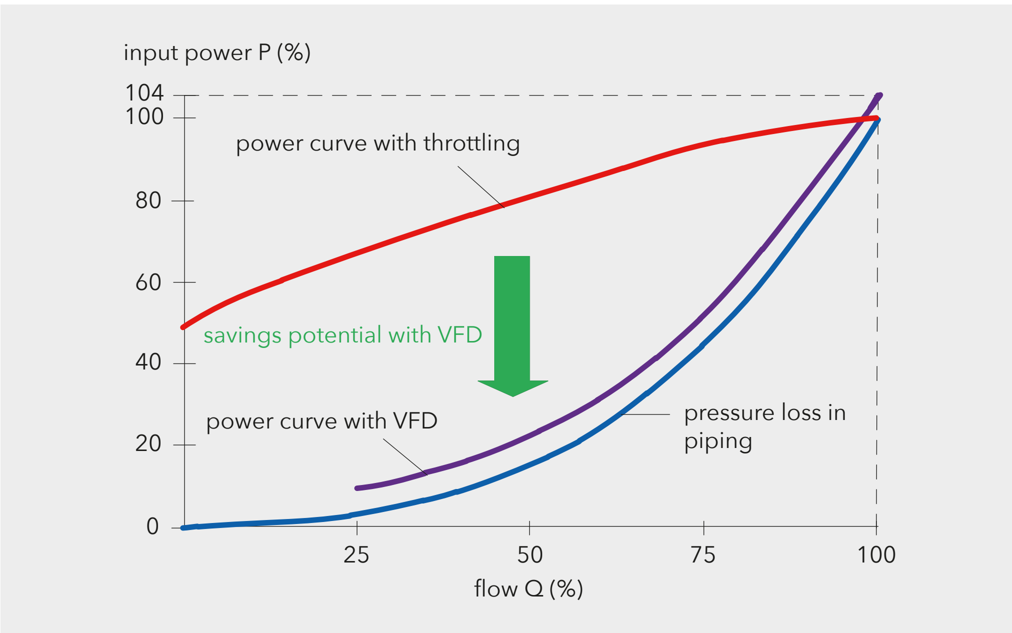


Figure 17: Savings potential of the use of a variable frequency drive for media delivery. (Source: Topmotors)

Important information on the use of variable frequency drives

- Where the power requirements of an application frequently vary, check whether it is suited to use of a VFD.
- Use VFDs only for properly sized motors; they are not a cure for oversized systems.
- The speed is controlled according to clear demand criteria with suitable sensors: pressure, temperature, flow rate, volume, etc.
- Legacy motors that were not designed for operation with VFDs may not be suitable for this purpose, as they present a risk of insulation defects.
- Select the setpoint parameters carefully in consideration of effective demand.
- The use of VFDs in electric motor-driven systems generates bearing currents, which can lead to premature bearing faults. Further information on this subject can be found in Topmotors Fact Sheet No. 31.

Disadvantages of variable frequency drives

Variable frequency drives do not of themselves save power. On the contrary: their energy conversion is not perfect and they generate additional inherent losses, which must be reduced. In addition, they generate harmonics on the electrical system, which must be taken into account during systems planning.

Topmotors Fact Sheet No. 25 provides detailed information on the operating principle of variable frequency drives, and their effects.

Variable frequency drive prices

Variable frequency drives are used to adjust motor torque and speed continuously to the required mechanical power. Since a VFD costs approximately the same as a motor, its use should be considered carefully. Like motors, VFDs vary widely in price. It is common, for example, for different discounts to be granted depending on the customer and the quantities ordered. Figure 17 shows prices for VFDs in CHF/kW as a function of the rated power. Up-to-date figures will be provided every two years in future Market Reports.

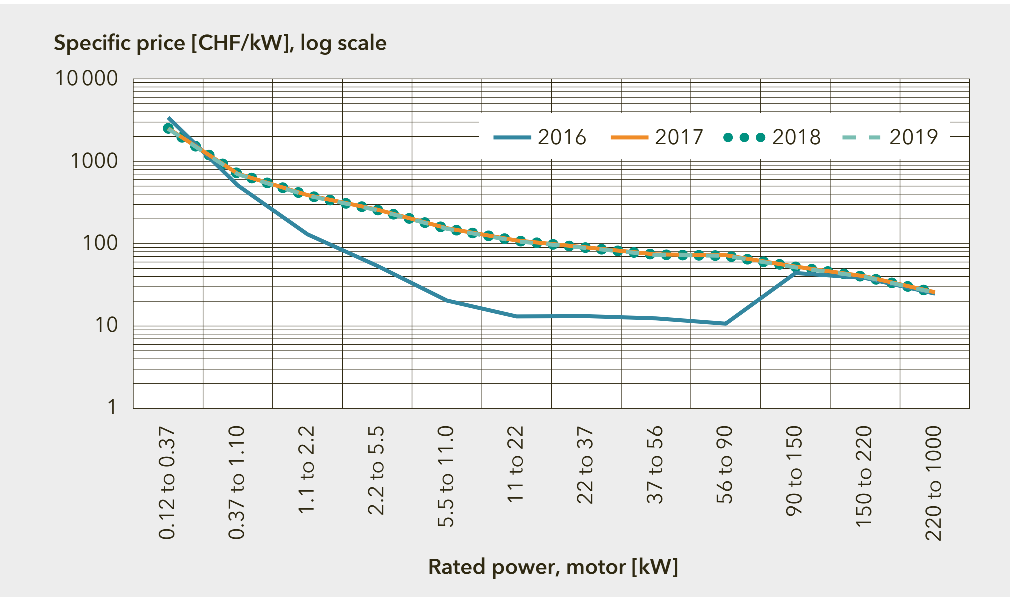


Figure 18: Specific price for variable frequency drives in CHF/kW, 2016–2019 (Source: Topmotors Market Report, 2020)

Additional information

Terms and units

Term	Abbreviation, formula symbol	Unit	Explanation
Electric motor-driven system	EMDS		Comprises CDM and motor
Extended product approach	EPA		
Variable frequency drive	VFD		Basic drive module (BDM)
Complete drive module	CDM		
International Electrotechnical Commission	IEC		
Power	P	W	
Power drive system	PDS		
Efficiency	η	–	Usually stated as a percentage

Standards, laws, regulations, sources

Standards

- IEC 60034-30-1:2014 Rotating electrical machines – Part 30-1: Efficiency classes of line operated AC motors (IE code).
- IEC TS 60034-30-2:2016 Rotating electrical machines – Part 30-2: Efficiency classes of variable speed AC motors (IE code).
- IEC 61800-9-2:2017 Adjustable speed electrical electric motor-driven systems – Part 9-2: Ecodesign for electric motor-driven systems, motor starters, power electronics.
- EN 50598-3:2015 Ecodesign for electric motor-driven systems, motor starters, power electronics and their driven applications – Part 3: Quantitative eco design approach through life cycle assessment including product category rules and the content of environmental declarations

Laws and regulations

- Energy Act, Ordinance of 1 November 2017 on the Energy Efficiency Requirements for mass-produced installations, Vehicles and Equipment (SR 730.02 Energieeffizienzverordnung EnEV, as at 1 July 2021), particularly Annexes 2.6, 2.7 (motors and VFDs), 2.8 and 2.9
- Commission Regulation (EU) 2019/1781 of 1 October 2019 laying down ecodesign requirements for electric motors and variable speed drives. Date of application with regard to the energy efficiency of motors and variable speed drives: 1 July 2021, see Article 12. Regulation (EC) No 640/2009 will be repealed as of 1 July 2021.

Sources

- Baumgartner, W. Massnahmen zum Stromsparen bei elektrischen Antrieben [Electricity-saving measures for electrical drives - Market analysis], Bern, 2006
- Topmotors: Fact Sheets Nos. 1-31, Website and Market Report 2020, Zurich, 2014 – 2020
- Förderprogramm EASY, Effizienz für Antriebssysteme [EASY programme, Efficiency for electric motor-driven systems], unpublished, Zurich, 2010 – 2014.

Further information

- www.topmotors.ch – the information platform for efficient electric motor-driven systems in Switzerland
- Topmotors Fact Sheets Nos. 1 to 31, Zurich, 2014 to 2020
- Topmotors Market Report 2020, Zurich, 2021
- Topmotors INFO Nos. 1, 2 and 3, Zurich, 2021

Editorial note

Topmotors Fact Sheet No. 32, Optimizing electric motor-driven systems, was prepared by Impact Energy in the course of the Topmotors implementation programme for efficient electric motor-driven systems. Topmotors is the information platform for efficient electric motor-driven systems in Switzerland, and is supported by EnergieSchweiz. The fact sheet was prepared by Rolf Tieben and Viktor Hangartner of Impact Energy. Editing and layout: Faktor Journalisten AG. The fact sheet is available in Italian, German and French at www.topmotors.ch.