TOPMOTORS FACT SHEET

No. 29

New motor technologies

The five key points

1. It is crucial that the motor is the correct size and is properly integrated into the overall motor driven system.
2. High efficiency asynchronous motors (IE3 or IE4) are best suited for long-running or continuous duty motors operating at a constant speed.
3. For motor driven systems in which the power or the speed changes: use a variable frequency drive (VFD) and a high-efficiency motor (IE3 or IE4).
4. For motor driven systems in which the power changes rapidly: use a high efficiency (IE3 or IE4) permanent magnet motor (PMM) or synchronous reluctance motor (SRM).
5. Hybrid PMMs and SRMs that are self-starting from the grid are also available. These are highly efficient during rated operation.

Objective and target audience

This Topmotors Fact Sheet No. 29 provides an up-to-date, systematic overview of the various electric motor technologies, their properties and energy efficiency within the motor driven system. It outlines the advantages and disadvantages of various motor technologies, such as the asynchronous motor (ASM), permanent magnet motor (PMM) and synchronous reluctance motor (SRM), compares them with one another and describes typical applications for the relevant technologies. The fact sheet is aimed at people with a technical interest (users, planners, installers, energy consultants, etc.) and manufacturers of components or entire motor driven systems.

Basics

Electric motors are responsible for approximately half the world's electrical energy consumption. They are the core element of all motor driven systems in pumps, fans, compressors, transport and process machines, etc. (Figure 1).

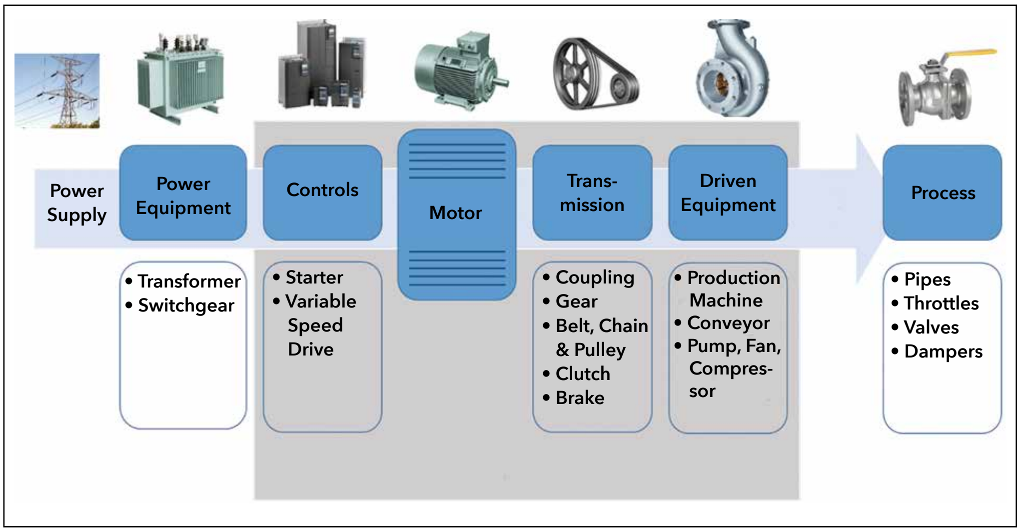

Figure 1: Driving unit and its components (Source: IEC 60034-31, 2019)

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Based on their characteristics, electric motors are classified into different categories:

- long-running or continuous duty motors operating at a constant speed (S1 category in IEC 60034-1) and with constant or, in some cases, changing load (torque)
- motors that change power (speed and torque) continuously using a VFD and in some cases also accelerate rapidly (e.g. car engines)
- motors with short and fast, in some cases reversible, rotations for positioning (servo motors)

Electric motors with 2 to 8 poles and rated output power of between 0.12 kW and 1000 kW are tested in accordance with IEC 60034-2-1 and classified in the following efficiency classes (IE-Code according to IEC 60034-30-1) based on their efficiency (Figure 2):

- IE4 Super premium efficiency
- IE3 Premium efficiency
- IE2 High efficiency
- IE1 Standard efficiency

The strong correlation between motor efficiency and rated output is important: in the overall scope of the IEC standard, the efficiency of a 4-pole IE3 motor ranges from approximately 65 % at 0.12 kW to 96 % at 1000 kW rated output power. In Switzerland, only IE3 motors and higher (or IE2 with a VFD) are currently permitted in new installations.

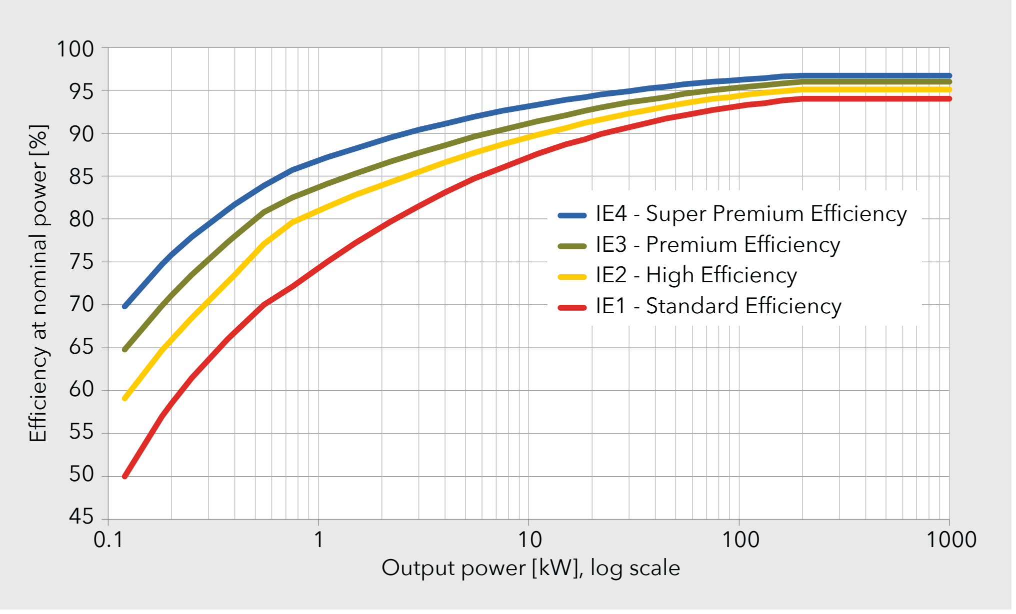

Figure 2: Classes of efficiency of motors according to IEC 60034-30-1, 4 pole, 50 Hz

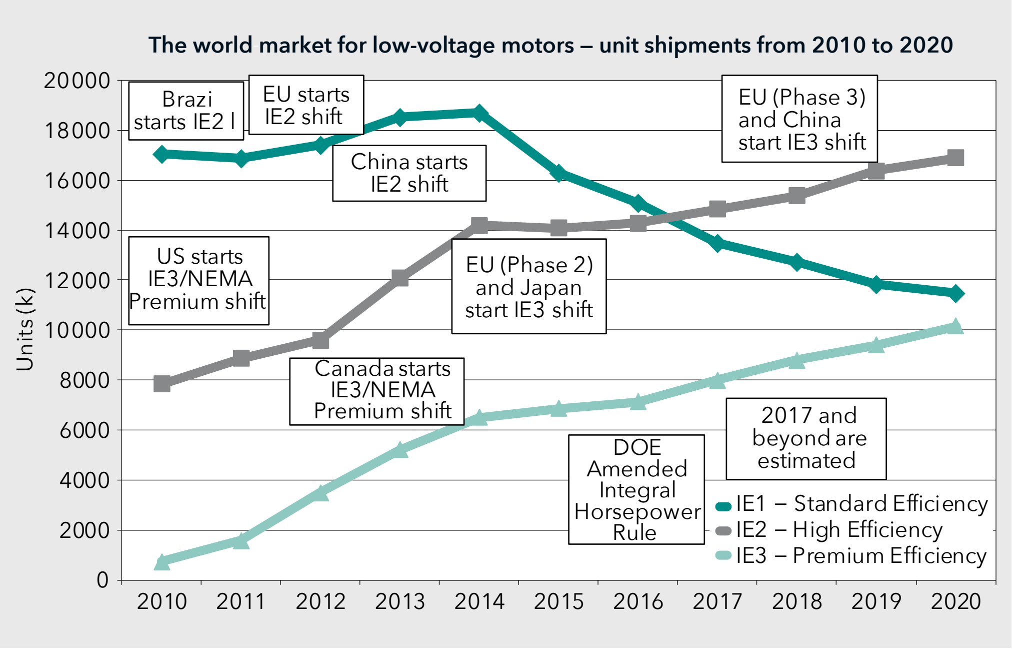

Figure 3: Evolution of the global motor markets: until 2016: market survey; from 2017: estimation (Source: Preston Reine, IHS Markit, in Motor Summit 2017, Zurich)

Motors that are tested with a VFD are inspected in accordance with IEC 60034-2-3 and classified according to IEC 60034-30-2 based on their level of efficiency. VFDs are tested in accordance with IEC 61800-9-2 since 2017 and classified in efficiency classes.

The efficiency of the motors used is important in systems with a large number of motors. In particular, if these motors are running almost constantly at full load, additional expenditure on efficiency generally pays for itself very quickly.

The global motor markets are shifting: the trend towards highly efficient motors and new technologies can not be stopped. Figure 3 shows the global move away from IE1 motors to increasingly more efficient IE2 and IE3 motors.

According to the Topmotors Market Report 2018, the motors by efficiency class, shown in Figure 4, were sold in Switzerland in 2017. It is clear that IE2 and IE3 motors dominate the market due to the minimum requirements they meet.

One positive development is that IE1 motors have almost disappeared from the market. Moreover, IE4 motors are continuously gaining market share. If we combine all the rated outputs, the dominance of efficient motors is even more evident (Figure 5).

However, many motors with an efficiency class of IE0 or IE1 are still operating in Switzerland today. Due to their obsolete technology, the potential for increasing the efficiency of these motors is significant compared to contemporary motors.

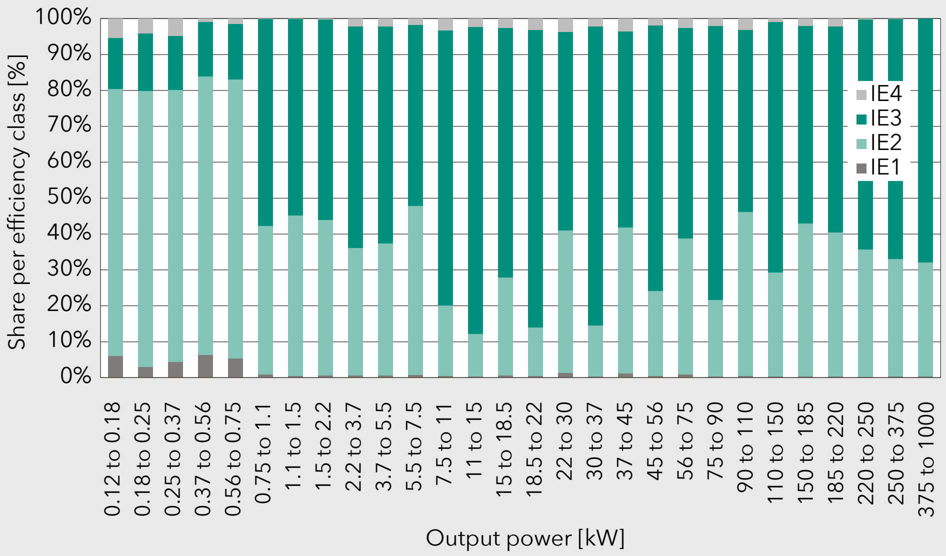

Figure 4: Motors sold in Switzerland in 2017 in accordance of efficiency class and nominal output power (Source: Topmotors Market Report, 2018)

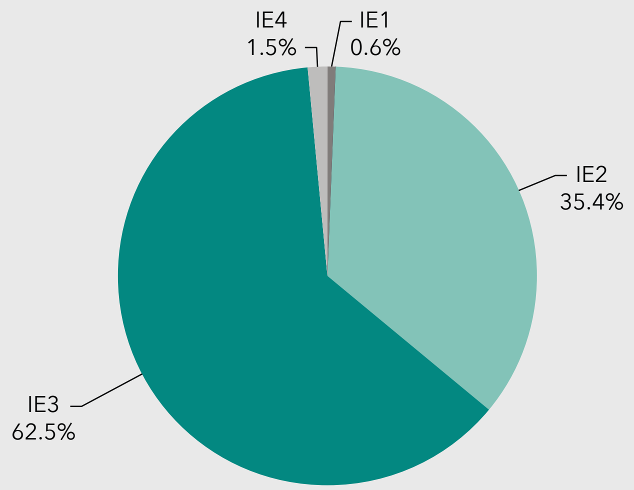

Figure 5: Efficiency classes of the motors sold in Switzerland in 2017 in the scope of the regulation about energy efficiency: 0,75 kW to 375 kW (Source: Topmotors Market Report, 2018)

Overview of motor technologies

As the following list of motor types shows, the 2008 EU Ecodesign Directive and the Swiss minimum requirements, which are based on this Directive, together with the demand for greater energy efficiency, have had an enormous effect on the market for efficient motors. Technical advances are still being made and offer even more optimisation potential. The user must be able to understand when the use of a controlled, highly efficient motor is appropriate and which motor technology is best suited to particular applications. The technologies differ according to:

1. Cost: cf. Table 1
2. Efficiency at different speeds: cf. Figure 6
3. Efficiency at different speeds and torques: cf. Figure 8
4. Weight: cf. Figure 7
5. Suitability for frequent and rapid starts
6. etc.

Cost

Each year, in the Topmotors Market Report, market studies are conducted on the cost of IE2, IE3 and IE4 motors. The specific price per kW of rated output power (irrespective of the motor technology) is calculated and the additional costs for more energy-efficient motors are presented (see Table 1).

Efficiency at different speed

Adapting the rotating speed to changing loads using a VFD can result in significant savings. However, it must be remembered that an VFD in itself does not save energy – quite the opposite in fact. Like any component in a motor driven system, an VFD is also subject to intrinsic losses, which have a negative effect on energy efficiency. It is necessary, therefore, to save more energy than the VFD additionally consumes by reducing the speed. However, it is precisely in closed systems like ventilation systems or pumping circuits that a reduction in speed has an effect on the power with the 3rd potency. Figure 6 shows the result of measurements on 2,2 kW motors using different motor technologies. The differences in efficiency are smaller if rated outputs are greater.

Class	IE2	IE3	IE4
Relative price	100%	113%	131%

Table 1: Comparison of the prices of the efficiency classes of motors: Average of the specific prices IE2, IE3, IE4 of each size between 0,12 kW and 1000 kW (Source: Topmotors Market Report, 2018)

Efficiency at different speed and torque

The various motor technologies display different characteristics when the load changes (speed and torque). Figure 8 presents the results of efficiency measurements on each of the motor technologies, including the VFD.

Weight

Based on the different motor technologies and associated materials, different weights are derived for the same rated output power. Depending on the application, this can be a factor in the motor layout and should therefore be checked and, if necessary, taken into consideration. Figure 7 shows the result of an analysis to examine the relative weight of individual motor technologies compared to an 11 kW IE3 asynchronous motor.

Suitability for frequent and rapid starts

Motors that are needed for frequent and rapid starts need to have a low mass inertia, i.e. a light rotor. Servo motors, as they are known, are used for functions with an exact angular position with controlled acceleration and rotational speed. A servo motor is a standard, high-performance electric motor (irrespective of its technology) with low inertia torque (narrow rotor) and a position feedback function.

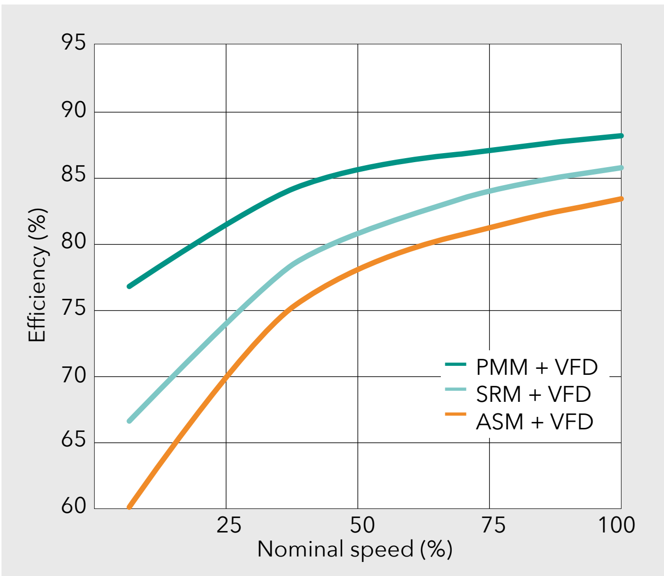

Figure 6: Efficiency comparison of four-pole motors with 2,2 kW, loaded with a torque of 7 Nm (Source: Jorge Estima/ EEMODS'17)

Asynchronous motor (ASM)

Even today, the ASM, which was developed by AEG in 1889, is the «workhorse» of the industry. It is extremely robust and reliable. The development of soft starters and frequency converters has significantly reinforced the trend for ASMs. The soft starter facilitates the smooth acceleration of a motor within the required period of time and consequently reduces the starting current. Once the motor has been started and the rated speed has been reached, the soft starter is generally bypassed; the motor is then directly connected to the mains. The motor can also be stopped for a predetermined time. A soft starter is therefore ideal for starting and stopping applications with a constant speed. If the motor speed is to be changed during operation, a VFD is required. In addition to allowing controlled starting and stopping, this also allows the motor speed to be controlled accurately, and in an energy-efficient manner.

The ASM is a simple form of induction motor and consists of a stationary stator in which the rotor turns. In most cases, the stator is also the housing and, in the case of electric motors, consists of a stack of steel laminations with slots, which act as a common core for the stator windings. The slots in the stator contain winding packs made from copper wire, which are connected according to the number of poles on the motor. The number of poles on the motor determines its synchronous speed.

As a result of phase shifting in the three-phase power supply, a rotating magnetic field develops in the stator, which affects the rotor. Smaller power outputs (< 2 kW) can also be operated using a capacitor at the single-phase 230 V power supply.

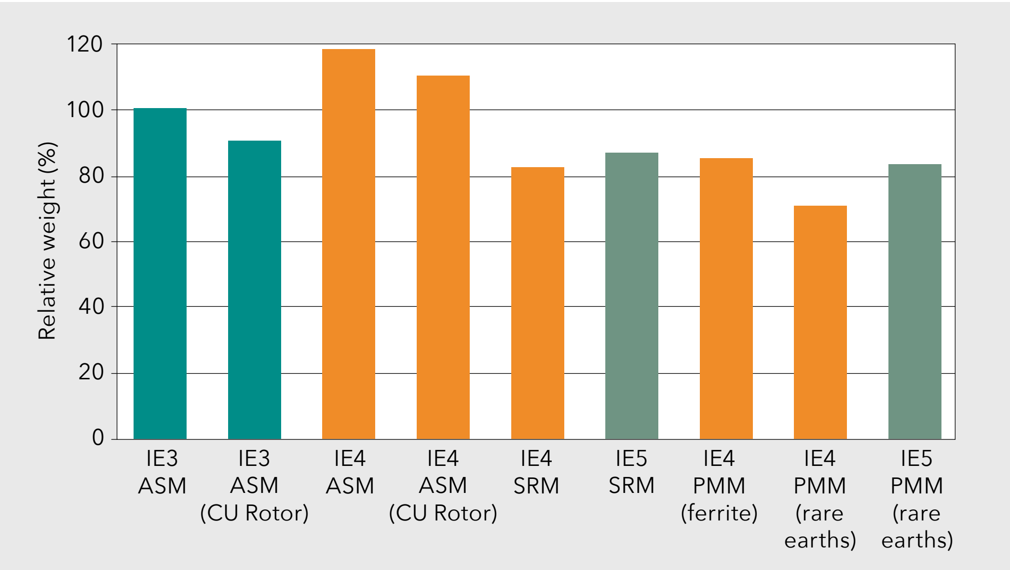

Figure 7: Weight comparison of motors with different technologies (Base = 100 %: 11 kW motors, IE3, ASM, 1500 U/min, aluminium housing) (Source: Anibal de Almeida, MS'18)

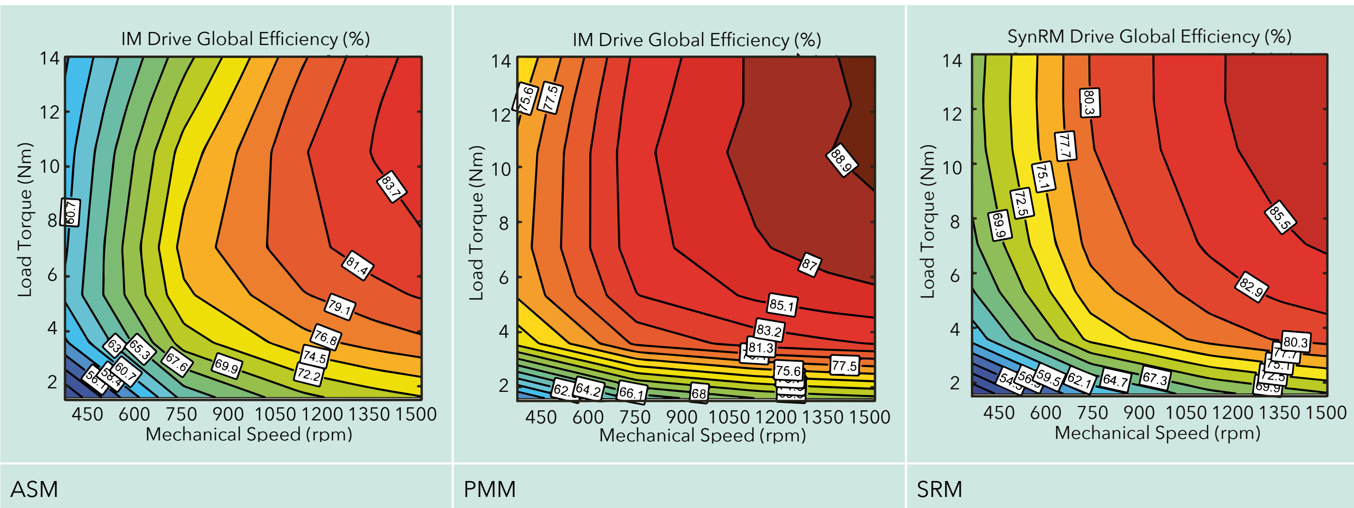

Figure 8: Curves for equal efficiency depending on torque and speed for asynchronous, permanent magnet and synchronous reluctance motors, all with VFDs, power 2,2 kW (Source: Jorge Estima/EEMODS'17)

The rotor in an electric motor consists of the shaft and the rotor winding. The winding usually comprises a stack of steel laminations in which copper or aluminium bars are embedded – this is known as the cage. A narrow air gap separates the rotor and stator. The rotating magnetic field in the stator induces a current in the rotor via the air gap. This forms a radial rotating magnetic field, which in turn causes the rotor to turn. This is called an induction motor due to the induced currents in the rotor.

Depending on the load, the rotor speed is slower than the speed of the stator's rotating magnetic field. The real speed of the rotor at the rated output is stated on the motor's rating plate. If the motor is idling, the speed is very close to the synchronous speed. The difference between the synchronous speed based on the power supply frequency (stator's rotating magnetic field) and the speed of the rotor (rated speed of the motor) is known as slip. The asynchronous motor is so named because it does not rotate synchronously with the power supply frequency of the stator's rotating magnetic field.

To improve efficiency, magnetically enhanced, larger or more metal sheets are often used to form the stator and the rotor. In practice, this can sometimes lead to motors with larger dimensions. However, all manufacturers are keen to comply with the standardised IEC frame and shaft dimensions (according to IEC 60072-1/-2/-3) in order to ensure compatibility with the widely used motors in existing systems. The standardised dimensions (foot spacing, shaft height, shaft diameter) are therefore generally identical, only the stator is sometimes larger (longer).

Before a motor is changed, it needs to be checked to see whether a replacement is actually needed. In many cases, a ten-year-old ASM may be sufficiently efficient, while other system components can be replaced more cost-effectively.

Essentially, the IEC 60034-30-1 motor standard assumes that, in principle, the IE4 efficiency class can be obtained with an ASM. It will be much more difficult to achieve IE5 with mains-operated motors.

A variant of the standard, high-efficiency asynchronous motor is the ASM with a copper cage in the rotor instead of an aluminium cage. It has the same structure and the same operating principle, but differs in terms of the rotor material. The copper winding has a lower electrical conductivity resistance than aluminium, thus reducing losses in the rotor. The motor can therefore easily achieve efficiency class IE3 or even IE4. The ASM with the copper rotor can also be operated directly from a power supply or using a VFD. Its design facilitates motors in the efficiency class up to IE4 in the IEC standard sizes. In some cases, this type of motor can achieve the required power even if it is smaller. The downside to these advantages are the disadvantages arising from the way in which such motors are manufactured. This is because the high melting point of copper (approximately 1100 °C) compared to aluminium (approximately 660 °C) requires higher-quality tools and pressure casting systems, increasing the material and manufacturing costs of the motor. Copper is also significantly more expensive than aluminium. Due to a lower resistance, motors with a copper rotor often have a higher starting current and a lower starting torque. This needs to be taken into consideration when designing and replacing older ASMs.

Number of poles	Pairs of poles	Synchronous speed n_{sync} at 50 Hz rpm
2	1	3000
4	2	1500
6	3	1000
8	4	750
10	5	600
12	6	500
14	7	429
16	8	375

Table 2: Synchronous speed according to number of poles

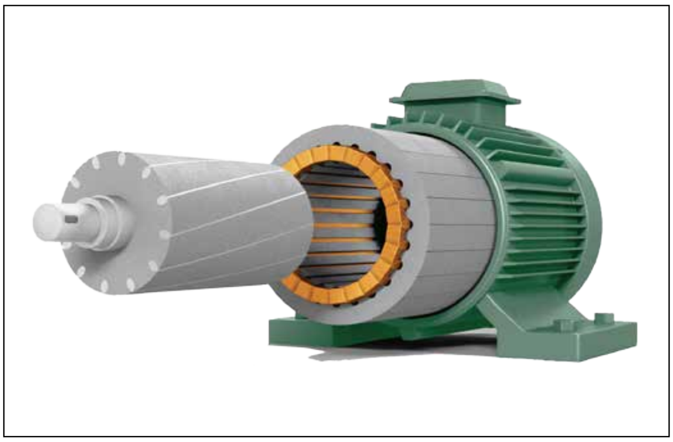

Figure 9: Schematic drawing of an ASM (Source: Danfoss)

The permanent magnet motor (PMM)

Unlike the ASM, the PMM has no rotor windings but rather permanent magnets, which are either attached to the rotor or embedded therein. In the simplest case, as with the ASM, the stator is designed as a three-phase distributed winding.

The PMM is a synchronous motor, which means that there is no slip between the rotor's and the stator's rotating magnetic field as there is with the ASM. The permanent magnets provide the necessary magnetisation for the entire motor, on a loss-free basis. This boosts the motor's efficiency compared to the ASM, whose higher copper (aluminium) content leads to stator and rotor resistance losses occurring as a result of the current required for magnetisation. This technique has long been used in servo motors. What is new here is the higher efficiency leading to use as an IEC standard motor and the corresponding structural shape.

For a short period between 2000 and 2010, prices for magnets were very high owing to the expensive rare earths required for their production. Today, rare earth prices have fallen significantly once again, because new rare earth mines have been developed or because cheaper replacement materials are available. Manufacturers are running tests to see if ferrite magnets can be substituted for rare earths, and initial tests are promising.

One disadvantage with the PMM is the need to install a VFD for operation. In addition, VFDs require position feedback to optimally align the magnetic field with the permanent magnets' position and induce rotation.

The PMM has two further drawbacks. First, there is a risk of demagnetisation with high currents and temperatures, which rarely occurs in practice. Second, there is a motor maintenance issue: the strong magnets in the rotor are difficult to remove from the stator for servicing, with special tools being required.

In practice, PMMs currently achieve efficiency classes of IE3 and IE4. Since PMMs can also be run in applications operating at constant speed without a VFD and their intrinsic losses can be managed economically, a special «line-start PMM» was developed. This is an ASM/PMM hybrid solution. It is equipped with a cage rotor where the magnets are embedded between the surface and the shaft. This results in a more elaborate rotor construction, making the motor more expensive. However, the line-start PMM offers a substantial advantage over a conventional PMM. It can be started and operated directly from the grid without a VFD, with the cage winding active during start-up. If the motor is accelerated to the specified speed provided via the power supply frequency, the line-start PMM behaves like a PMM and operates synchronously.

This form of start-up also has a drawback: upon start-up, the motor may run backwards briefly (for maximum half a pole pitch). This alternating torque at start-up also occurs when the ASM is operated from the grid, but it is much more pronounced with the line-start PMM. Furthermore, the torque peaks at start-up can be very high – up to 17 times rated torque in extreme cases. This motor type is not suited to heavy starting and does not have a high dynamic. In addition, load peaks or slight overloads can cause the motor to lose synchronicity, thereby drastically reducing efficiency. It is also sensitive to undervoltage, which can occur with mains fluctuations.

With mains operation, line-start PMMs achieve efficiency classes of IE3 and IE4. It should be noted that with primarily VFD operation, the efficiency rating frequently falls by 5 – 10 % compared to mains operation. This is due to the cage winding, which acts as a damper winding. The available structural forms comply with the IEC standard or are somewhat smaller. In addition, this motor poses a rare earth sourcing problem, because permanent magnets are used here as well. Introducing a line-start PMM requires critical assessment, because the IE4 efficiency class can also be reached with a copper ASM.

Figure 10: Two PMMs, on the left with embedded magnets, and on the right with surface-mounted magnets (Source: Danfoss)

The electronically commutated motor (ECM)

In practice, ECMs come in many different variants. For example, they may be small, low-watt servo motors, but are also used in heating, ventilation and air conditioning systems as external rotors in fans or in circulation pumps. Manufacturers often claim very high efficiency for these motors. This applies primarily to microdrives, where ECMs are significantly superior to universal or shaded-pole motors (efficiency rating below 30 %). Depending on the model, the efficiency rating of current ECMs is comparable to IE2 to IE4 ASMs.

Like the PMM, the rotor is equipped with magnets and the stator carries the three-phase windings. In the original concept, the ECM worked with an electronically commutated direct current (DC), which always flows only between two circuits, hence the name brushless DC motor (BLDC) or electronically commutated motor (ECM). Technologically speaking, the BLDC belongs to the category of AC motors. Consequently, the name BLDC can be slightly misleading. To offset the disadvantages of the BLDC concept, such as higher phase current and torque ripple, manufacturers have developed better control procedures. Sensorless processes are already available. Both concepts – the BLDC and the new pulse width modulation-sinusoidal actuator (PWM) come under the heading of ECMs. This means that users must determine whether they are dealing with a BLDC or an improved, PMM-like concept. Owing to the presence of permanent magnets, the same determinants apply with regard to rare earths and maintenance as with the PMM.

The synchronous reluctance motor (SRM)

Another variant of three-phase motors is the synchronous reluctance motor, or SRM, which operates without expensive magnets. It uses the reluctance generated by the rotor-position dependent changes in magnetic resistance. This technique is not new, but is coming onto the market once again. This is due to the fact that in the past, manufacturers were not able to make these motors sufficiently energy-efficient. Specially cut rotor laminations guide the magnetic lines inside the rotors, producing energy-efficient reluctance torque. In practice, this produces efficiency ratings between IE2 to IE4, and closer to IE2 at lower powers. These motors only achieve IE4 efficiency class from around 15 kW upwards. They are also well suited to lower rotational speeds. SRMs require VFDs for mains operation, just like PMMs. At present, these motors are still characterised by relatively high costs. However, rising unit quantities are expected to bring prices down, given that design and production are relatively simple.

Like the line-start PMM, the direct-on-line (DOL) SRM relies on the principle of the cage rotor. To do so, it fills open spaces in the rotor laminations with aluminium, shorting these at the ends. Here, the major advantage is that this motor can be started and operated directly from the grid. At the same time, it offers a better cos φ. The disadvantage is that the additional damping of the cage windings once again generates higher losses in VFD operation.

Advantages and disadvantages of modern high-efficiency motors

In principle, higher motor efficiency helps save electrical energy. The resulting frequently occurring additional costs must be offset by energy cost savings in operation. With over 2 000 operating hours per year, this generally takes less than five years. In addition, correct sizing and load-matching operation are always advantageous and reduce overall costs. Some motor technologies offer an opportunity to use smaller, lighter motors featuring the same performance and higher efficiency. Lower losses, hence lower temperatures, generally have a positive impact on technical service life and operating costs.

With increasing efficiency, the rated speed for ASMs and PMMs has risen slightly. This is due to the lower slip between power supply frequency and rotor speed. When an old motor is replaced across the board by a similarly-sized new motor (without VFD operation), it should be noted that for example pumps and fans operate at a slightly higher speed and thus move more air or water. Despite more efficient motors, this can lead to higher electrical power consumption (the speed is cubed). This effect can be avoided by adapting the transmission (gear ratio) or using an VFD.

The saving from the transition from IE3 to IE4 is smaller than the transition a few years ago from IE1 to IE2, which means that the marginal benefit of even higher efficiency is declining.

Owing to higher purchase costs or utilisation with many

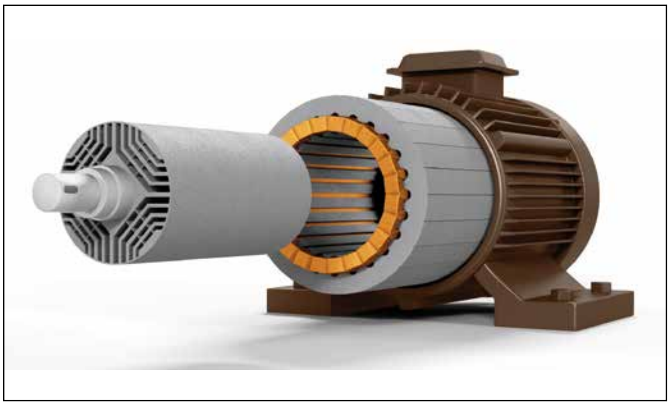

Figure 11: Schematic drawing of a SRM (Source: Danfoss)

load cycles due to possible high moments of inertia, an IE4 motor may not be suitable for all uses. However, a PMM can be built with a lower mass moment of inertia than an ASM.
Some of the drawbacks of the different motor technologies can be remedied through optimisation – for example start-up performance via PMMs that start directly from the grid (line-start).
Optimisation must cover the entire motor driven unit (motor, VFD, gears, transmission and application). A good motor by itself is not enough to achieve better efficiency throughout the system, and other measures might offer a cheaper means of improving overall system efficiency. These include more precise sizing, good coordination between the individual components, better load-matching in operation, direct drive instead of transmissions and gears, and greater efficiency of the application (pumps, fans, compressors) etc.

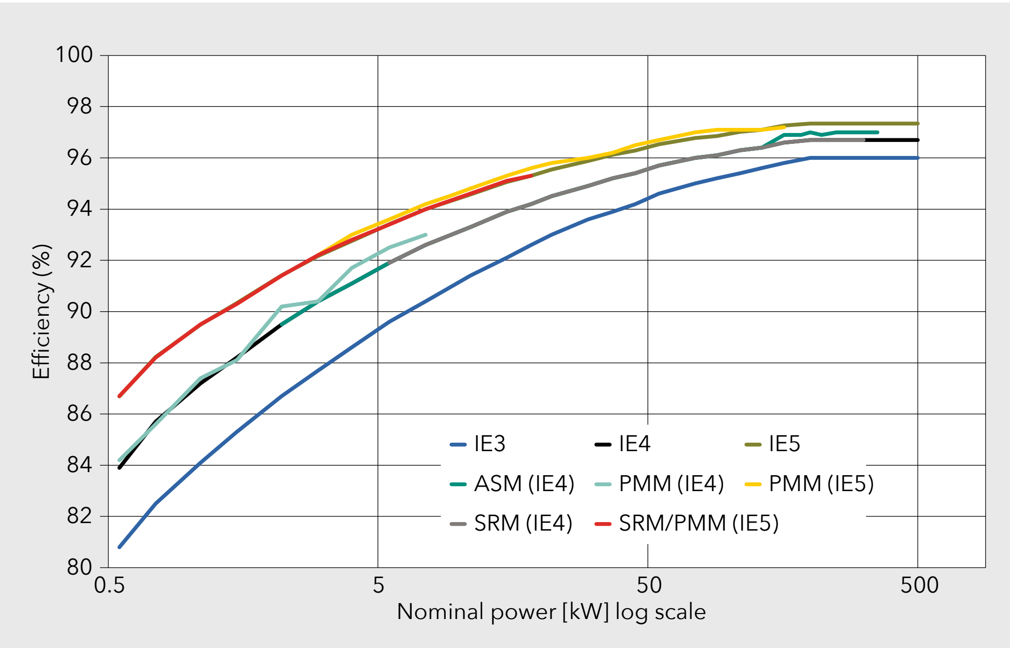

Figure 12: Measurement data for different motor technologies compared with IE classes (Source: Anibal de Almeida, Motor Summit 2018)

Additional information

Terms and units

Designation	Abbreviation	Unit	Indices, explanation
Asynchronous motor	ASM		
Permanent magnet motor	PMM		
Electronically commutated motor	ECM		Motor with electronic commutation
Brushless DC motor	BLDC		
Synchronous reluctance motor	SRM		
Variable frequency drive	VFD		also: VSD (Variable speed drive)
Direct-On-Line	DOL		50 Hz (or 60 HZ) from the grid
Line-Start			Start from the grid (without VFD)
Hybrid	possible with DOL or VFD		
Direct Current	DC	A	direct current
Alternating Current	AC	A	alternating current
Power	P	kW	e: electrical m: mechanical
Efficiency	η (eta)	-	
Torque	M	Nm	
IE-Code	IE1, IE2, IE3, IE4		Efficiency classes of electric motors in accordance IEC 60034-30-1

Standards and regulations

IEC standards for efficiency classes of motors and tests of efficiency

	Motor with constant speed	Motor with variable speed	VFD
General conditions, tolerances	IEC 60034-1	IEC 60034-1	
Test of efficiency	IEC 60034-2-1	IEC 60034-2-3	IEC 61800-9-2
Efficiency class	IEC 60034-30-1	IEC 60034-30-2	IEC 61800-9-2
Dimensions	IEC 60072-1/-2/-3		

European regulations

- Commission Regulation (EC) No 640/2009 of 22 July 2009 implementing Directive 2005/32/EC of the European Parliament and of the Council with regard to ecodesign requirements for electric motors, Brussels, 2009, Revision pending

Swiss minimum requirements

- The relevant regulation is called EnEV (Energieeffizienzverordnung = Energy Efficiency Ordinance; regulation on the requirements of energy efficiency of mass produced systems, vehicles and appliances). The ordinance and all relevant annexes are coordinated with the corresponding European Ecodesign Directives (available in German, French and Italian). Since 1 January 2017, only electric motors from the premium efficiency class IE3 from 0.75 kW to 375 kW, or IE2 together with a VFD, have been approved for sale in Switzerland.

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- Impact Energy: Topmotors Market Report 2018, Zurich (unpublished, will be published at the beginning of 2019)

Editorial remark

The Topmotors Fact Sheet was produced by Impact Energy in conjunction with Topmotors' implementation program for efficient motor driven drive systems. It was prepared by Conrad U. Brunner (iE), Michael Burghardt and Norbert Hanigovszki (Danfoss), Prof. Andrea Vezzini (BFH), Jürg Nipkow (ARENA), Rolf Tieben and Petar Klingel (iE). Copy-editing and graphic presentation: Faktor Journalisten AG.