EuP Lot 30:
Electric Motors and Drives

Task 6: Technical analysis of Best Available Technologies (BAT)

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6 Introduction

This section entails a general technical analysis of the best available technologies for products, as defined in section 1. It provides general inputs for the identification of improvement potential when compared to the BaseCases.

6.1 Small induction motors

Joule effect losses are normally dominant in small motors. I^2R losses can be reduced by reducing resistance to current flow in the electrical components of a motor. The resistance is dependent on the resistivity of the material used and its geometric dimensions. Resistance is inversely proportional to the cross-sectional area of the material through which current is flowing. Options to reduce I^2R losses in inductions motors include:

- Increasing the cross-section of stator windings - 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.
- Use copper rotor bars – Due to the excellent electrical conductivity of copper (57 MS/m compared to 37 MS/m), 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.
- Increase size of the end rings.
- Reduce rotor bar skew - rotor bars are slightly skewed which helps reduce harmonics Reducing the skew will help reduce the rotor resistance and reactance, thereby providing gains in efficiency. However, care must be taken not increase harmonics. Odd harmonics, can originate cogging and higher magnetic noise.
- Reduce the air gap between the stator and rotor - A smaller air gap lowers the magnetizing current the motor draws to maintain the magnetic field across that gap. The motor will then require less current to drive the load and thereby reduce I^2R losses. Mechanical boarders (tolerances) and the increase of harmonics limit the reduction of airgap.
- For single-phase motors, adding a secondary “run” capacitor - These motors have two capacitors in series with the main stator winding. The starting capacitor is connected in series with a centrifugal switch. The starting capacitor optimizes starting-torque during the starting period, while the running capacitor optimizes the motor's current flow leading to better energy efficiency when operating at running speed. When the motor initially starts with the centrifugal switch in the closed position, both capacitors are functional. Once the motor gets to about 70%-to-80% of normal operating speed, the switch disconnects the starting capacitor. Since the run capacitor is NOT wired in series with the switch, the run capacitor remains functional to optimize the motor's performance. This design provides optimum levels of both starting-torque and efficient running characteristics

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 flux-density. Options to reduce magnetic losses are:

- Lengthening the lamination stack - reduces the flux density within the stack, therefore reducing core losses.
- Use of magnetic steel with better magnetic properties - hysteresis losses are reduced because the magnetic permeability improves and grain size increases, reducing the magnetic domain resistance. Eddy currents are reduced because the resistivity of the laminations is higher, reducing the magnitude of the currents.
- Reduce the laminations' thickness - using thinner laminations decreases the cross-sectional area through which the eddy currents are produced, reducing the magnitude of the eddy currents.
- Ensuring adequate insulation between laminations, thus minimizing the flow of current (and I^2R losses) through the stack and reducing eddy current losses.
- Annealing the core steel - After being annealed, the material becomes much easier to magnetize, which means the magnetic domains reorient more easily reducing hysteresis losses. Annealing is a heat process whereby a metal is heated to a specific temperature and then allowed to cool slowly facilitating the diffusion of atoms within a solid material to relieve internal stresses and refine the structure by making it homogeneous.

Mechanical losses are caused by friction in the bearings, ventilation and windage losses. Options to reduce mechanical losses include:

- Use low friction bearings – These bearings take advantages of better geometry, materials and lubricant to reduce friction by more than 30% when compared to standard bearings
- Improved cooling – properly designed cooling systems, such as optimized fans, can help reduce ventilation losses. Improved air flow can also help reduce the power required to move the fan.

6.2 Electronically commutated / synchronous permanent magnet motors

An Electronically Commutated (EC) motor also called Brushless DC (BLDC) 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. The motor rotates in synchronism with the magnetic field, thus eliminating I^2R losses in the rotor (no rotor slip losses).

These motors typically require an electronic frequency converter. The AC supply is converted to a DC supply, which feeds a Pulse-Width Modulation (PWM) inverter, which generates a set of three-phase almost sinusoidal waveforms, supplied to the stator windings. To rotate, the stator windings should be energized in a sequence. It is important to know the rotor position in order to understand which winding will be energized following the energizing sequence. and a rotor position sensor (encoder) for proper operation. In some designs the encoder can be replaced by a control algorithm in the converter. Rotor position is sensed using Hall effect sensors embedded into either the stator or the rotor, but new sensorless designs are becoming available.

Based on the required magnetic field density in the rotor, the proper magnetic material and geometry is chosen to make the rotor.

Permanent Magnet Motors are a type of synchronous motor. 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.

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).

In the low power range and in applications requiring variable speed control EC/BLDC motors can lead to significant efficiency improvements when compared with variable speed induction motors, as shown in Figure 6-1.

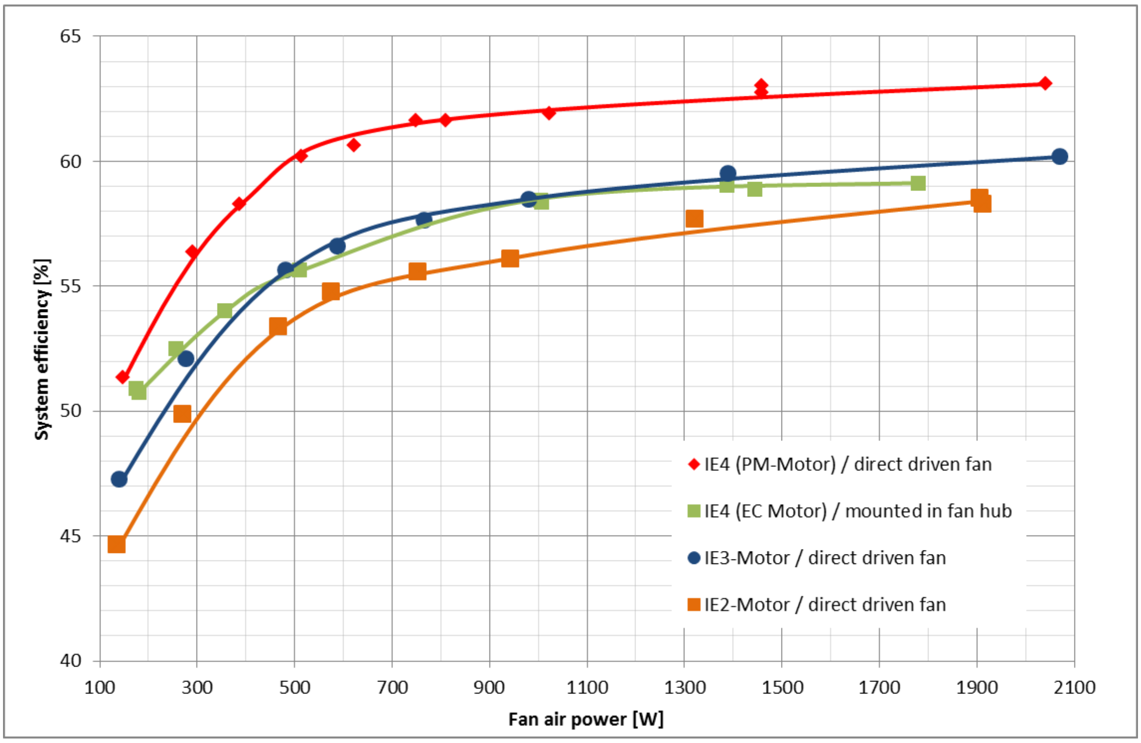

Figure 6-1 Energy efficiency of IM and PM motors in ventilator systems [11]

Some manufacturers sell integrated PMSM+VSD solutions, which achieve full-load efficiency values significantly higher than IE3 class [1].

6.3 Line start permanent magnet motor (LSPMM)

Another very high efficiency technology that has recently been introduced in the market by some manufacturers is the line start permanent magnet motor (LSPMM). 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.

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 [2].

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.

Although in Table one of the IEC 60034-30-1 draft standard they are identified with “Difficult” for IE4 class and “No” for IE5 class, there are already commercially available LSPMs that meet IE4 levels, and are actually candidates to IE5 class.

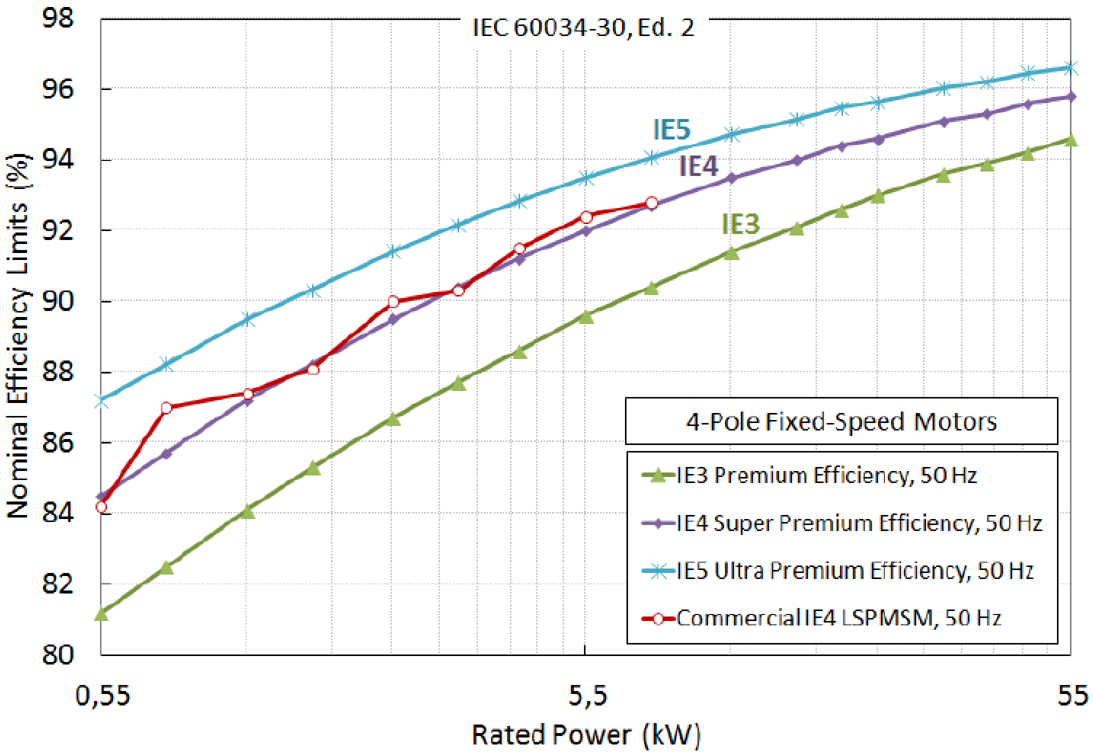

Figure 6-2 Rated efficiency levels for commercial 50-Hz, 4-pole LSPMs from 0,55 kW to 7,5 kW and IE3-, IE4- and IE5-class limits defined in the draft of the IEC60034-30-1 Standard [3]

In the early stages of LSPMs development, one of the main initial drawbacks was the starting torque, particularly in loads combining high starting torque and high inertia. Presently, commercial LSPMs can have a maximum allowable load inertia limited to 30 times the motor inertia, which is enough for most industrial loads. The starting torque of commercial 4-pole LSPMs is 2.2 to 2.8 times higher than rated torque for the 0.55-7.5 kW power range. [3]

It is worth noting that the starting “kick” of LSPMs is quite violent, which can lead to accelerated mechanical wear of the motor and load bearings and/or gears (if present). This can be particularly critical in application with frequent start/stop cycles and is one of the major disadvantages of LSPM motors.

A high counter-torque and a high inertia cannot be started at the same time. During start-up, strong oscillating torques create noise and vibration. Therefore, such motors are especially suitable for pumps, fans, compressors and similar applications, i.e. whenever the torque is a function of the square of the speed. They can also be used for conveyor belts due to the low inertia of such applications, provided the starting torque is sufficient. LSPM motors are less suited for hoist drives, lifts and other applications, where overloads can occur and lead to critical situations. In particular, under-voltage is critical and can lead to a loss or failure of synchronization [10].

Permanent magnets

Ferrite magnets have traditionally been used to make permanent magnets in low cost applications. As the technology advances and with decreasing costs, rare earth elements (REE) 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, Ferrite 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.

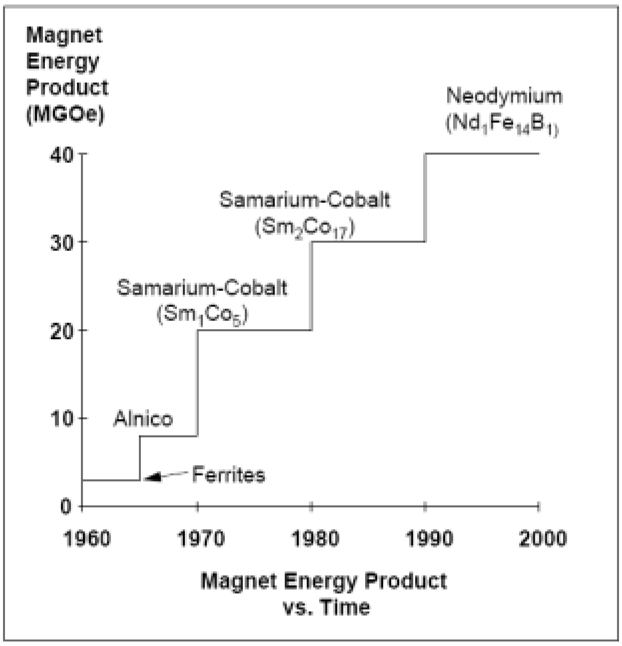

Figure 6-3 Advances in magnet energy product [4]

Some manufacturers have been able to produce motors, based on an innovative geometry for the motor rotor and stator, using less costly ferrite magnets to deliver the performance level typically found in much more expensive rare earth-based permanent magnet motors.

The production of rare-earth alloy permanent magnets for use in these motor technologies presents two problems: (1) the limited supply of REE and (2) the environmental impact of mining and refining these elements.

Although there is currently no inequality between supply and demand of REE if the predicted trend in demand of REE for the production of both electric motors and generators persists will there is no doubt that total REE supply will eventually lag behind total demand [5] [6].

For example, Dysprosium is an essential element in the production of neodymium magnets, which are the most commonly used type of rare-earth magnet in motors, allowing them to maintain their properties at high temperatures.

Past supply has generally been able to keep up with past demand, but current growth rates in production are simply too low to yield future equality, and the necessary ramp-up of production is difficult to achieve . China's Ministry of Commerce (MOC) has recently reduced its export quotas for REEs. China produces 98% of the world's dysprosium, thus changes in China's export policy could severely reduce global dysprosium supply affecting the security of supply. As dysprosium is a heavy rare earth, it exists in much lower concentrations than other . It is therefore hard to ramp up production of dysprosium while still maintaining economic viability. Finally, although many new mines are coming online within the next few years (Lynas and Molycorp), their focus is exclusively on mining light REEs. Thus, the increase in supply due to their increasing production will have almost no effect on net dysprosium supply [6].

Another issue is that REE are mined as a combined ore, and then later separated through chemical processing. Thus, it is impossible to increase production of a given REE without also increasing production of other REEs, although demand can be different.

The mining of REEs also presents a number of environmental concerns. Most rare earth elements are mined through open pit mining, which necessarily causes a disruption to existing ecosystems, involving the loss of wild life habitat, loss of vegetation and alterations in water runoff. The contamination of water supplies through sedimentation, acid drainage, and metals deposition through the production of small, fine particles (tailings) that can be absorbed into the water and ground surrounding a particular mine. If a mining project involves the extraction of a few hundred million metric tons of mineral ore, then the mine project will generate a similar quantity of tailings. The proper disposal of this high-volume toxic waste material is of major importance.

Additionally, the ores containing REEs often contain less savory components such as radioactive thorium and uranium and often contain undesired toxic metals (such as cadmium, lead, and arsenic). These components need to be safely isolated and stored.

Because extracted metal ores need to be purified they undergo a process of refining (beneficiation). This refining process introduces another set of environmental concerns, mostly revolving around the release of metal byproducts into the environment. It is very easy for metals to enter the air, ground, or water sin an environment, and once there it is nearly impossible to remove them.

The environmental consequences that any specific open pit mining operation will have on the natural and cultural environments depends on a number of factors: type of rock and ore being mined, scale and longevity of mining operations, efficiency and effectiveness of environmental management systems and mitigation measures that are employed by mine management, the nature and level of enforcement of government environmental regulations, and the sensitivity of the receiving environment (especially the abundance/scarcity of both surface and ground waters).

Although mining is heavily regulated in developed countries, these laws differ from country to country, making it difficult to quantify the real impacts of REE mining activities, particularly for developing countries.

6.4 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) [7].

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.

Unlike induction motors, switched reluctance motors require a power converter circuit, controlling the phase currents to produce continuous motion and torque. Rotor position feedback is 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.

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

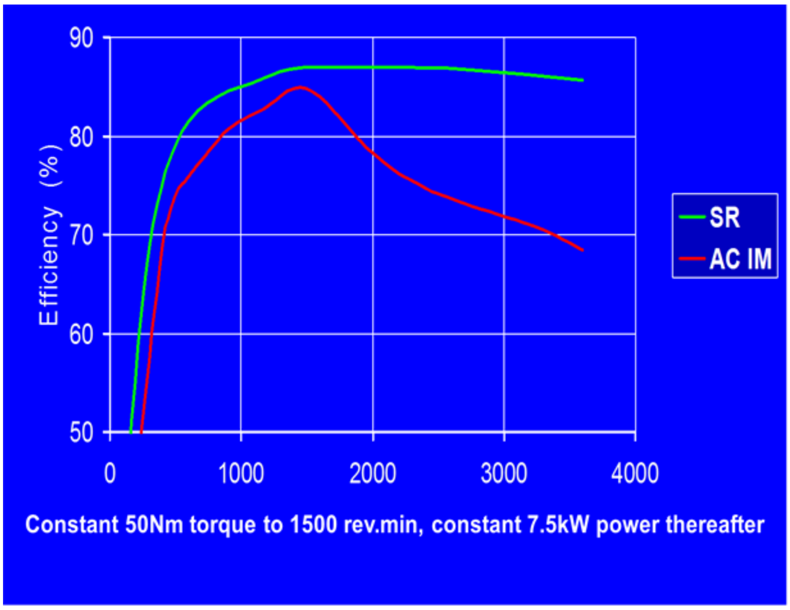

Figure 6-4 System Efficiency of a SR motor versus induction motor driven by a VFD

6.5 Synchronous Reluctance Motors

Synchronous reluctance motors operate based on the same principle as switched reluctance motors the main difference being rotor design. The rotor has an equal number of poles as the stator and the rotor teeth are arranged to introduce internal flux “barriers,” holes which direct the magnetic flux along the so-called direct axis.

The rotor design eliminates rotor cage I^2R losses. These motors require an electronic controller (VSD) to operate.

6.6 Brake Motors

Brake motors are electric motors with a mechanical brake fitted at one end.

In most applications, electric motors are not required to stop immediately, instead, electric motors typically slow down and gradually stop after power is removed from the motor, due to a buildup of friction and windage from the internal components of the motor. However, some applications require electric motors to stop quickly. Such motors may employ a brake component that, when engaged, abruptly slows or stops shaft rotation. The brake component attaches to one end of the motor and surrounds a section of the motor’s shaft. During normal operation of the motor, the brake is disengaged from the motor’s shaft—it neither touches nor interferes with the motor’s operation. However, under these conditions, the brake is drawing power from the electric motor’s power source and may be contributing to windage losses, because the brake is an additional rotating component on the motor’s shaft. When power is removed from the electric motor (and brake component), the brake component de-energizes and engages the motor shaft, quickly slowing or stopping rotation of the rotor and shaft components.

Brake motors are often used in intermittent duty applications where quick stopping is required (e.g. automatic machinery, packaging machinery, machine tools, hoisting equipment, etc.). In some of these applications special requirements may be needed such as: heavy starting duty, special torque stiffness and/or breakdown torque characteristics, large number of starts/stop cycles, low inertia, limited starting current.

For applications with a large number of start/stops the increased rotor inertia of a more efficient motor increase the run-up time and the power-consumption during run-up. It will also reduce the permissible number of starts per hour thereby possibly limiting the application’s throughput. Furthermore, when braking is performed by a mechanical braking system, both the wear of the brake disc and the braking-time will increase for motors with higher rotor inertia [8].

Brake motors are capable of achieving the same efficiency levels as induction motors alone.

6.7 Explosion-proof motors

Explosion-proof motors are motors built for operation in environments that contain combustible materials. Because of this the motor must have several special features:

- be constructed in such a way that it will be able to completely contain an internal explosion without rupturing

- any hot gases escaping the enclosure are forced to exit through long, narrow openings known as flame paths
- must not develop surface temperatures hot enough to cause spontaneous ignition of hazardous gases in the external atmosphere
- no sparking parts can be used

As a result of safety requirements explosion proof motors may face design constraints such as increased air-gap, reduced starting current, enhanced sealing, etc., which have a negative impact on efficiency. Nevertheless, for lower explosion proof levels, higher efficiency classes such as IE3 are possible.

Explosion proof motors require ATEX certification. This certification has to be applied for at an official authority (i.e. PTB/Germany) and may limit the use, allowed environment or allow combination possibilities with other components such as drive controllers.

6.8 Borehole Pump Motors

There are some permanent magnet borehole pump motors, but these require a controller and do not command a significant market share at present. Because they are used in high static head applications, the scope for speed reduction is only modest, but speed control is still used as an efficient solution to regulating water extraction. Currently the UK is seen as the biggest market for variable speed control.

6.9 VSDs

VSD energy consumption depends on the losses in the control circuits: motor control, network connection, Input/Output (I/Os), logic controllers and particularly in the output-switches (30-50%). These losses may vary depending on the capabilities of the VSD.

VSD losses are mainly influenced by the switching frequency (the higher the switching frequency, the higher the losses in the drive) and the output current (which is function of output power and load). However low switching frequency can cause torque ripple.

Transistors - IGBTs (Insulated Gate Bipolar Transistors) and MOSFETs (Field Effect Transistors) - have nearly completely replaced thyristors in inverter circuits below 1 MW. Overall losses, parts count, and driver cost are markedly reduced with these devices resulting in an increasingly competitive product.

The functionality of the drive can also negatively affect its energy consumption but at the same time increase the capability of the system it is integrated and its efficiency either by reducing its energy consumption or by increasing its throughput. VSD capabilities can vary from simply varying motor speed with simple open-loop algorithms, to very complex enhanced on-board software features and embedded PLC functionality, network communications, etc.

It must be noted that the energy benefits from using a VSD always come from decreasing the losses of the system on the load side and that if this benefits can be achieved they surpass the losses in the drive itself.

Harmonics can affect the equipment performance and are both caused by and can interfere with the function of VSDs. Harmonics increase equipment losses and have also raised concerns about excessive currents and heating in transformers and neutral conductors. Harmonic waveforms are characterised by their amplitude and harmonic number. Figure 6-7 shows how the 50 Hz fundamental changes when harmonics are added.

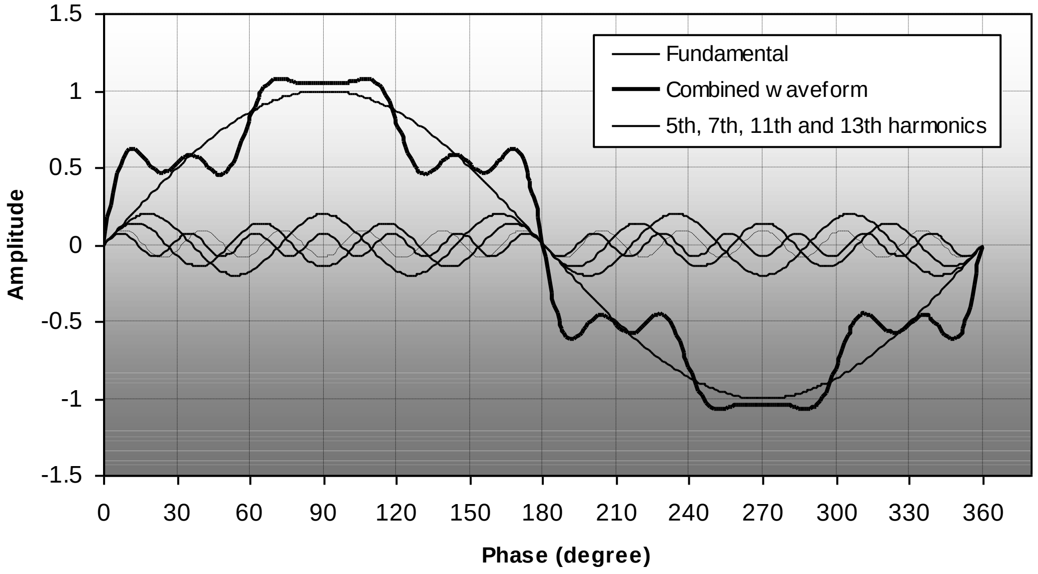

Figure 6-5 Waveform with VSD harmonics: Combined waveform reflects combination of fundamental and harmonics [9].

The harmonics are usually measured not individually, but collectively as total harmonic distortion (THD) which is the RMS value (square root of the sum of the squares) of all the harmonic frequencies, divided by the RMS value of current or voltage.

Line side harmonics caused by VSD´s can be reduced by integrated harmonics filters (i.e. to a level of 40% THdi which will take out most of the energy relevant harmonics like the 5th, 7th, 11th). Additionally, it is possible to employ external passive or active filters which will bring down the THDi level to 5% or less. VSD drives typically employ a B6 rectifier which will extinguish large parts of the harmonics produced by other non-linear loads with a B2 rectifier as being used by switched power supplies for building light, PC´s, etc.

Motors fed from a converter present additional losses, higher than during operation on a sinusoidal system. These additional losses depend on the harmonic spectrum of the impressed supply quantity (either current or voltage) from the converter. Additionally, harmonics may cause significant damage to the motor by producing bearing currents and insulation voltage stress. These problems can be mitigated by:

- Keeping the link motor-VSD as short as possible;
- Proper grounding;
- Proper shielding;
- Passive or active harmonic filters;
- Isolation transformers.

Sophisticated control techniques have been developed in modern PWM-VSDs, to minimize harmonics, particularly on the motor side.

The most efficient VSDs present in the market today have approximately 25% lower losses than the average product on the market as defined in Task 5.

6.10 Conclusions

There are a number of options to improve the efficiency of small motors both for single-phase and poly-phase motors. It is important to notice that most options involve the use of more active materials

In recent years, the area of energy-efficient motors, in the medium power rang (0,75 kW up to 375 kW) has experienced a fast evolution of motor technologies as shown in the figure below.

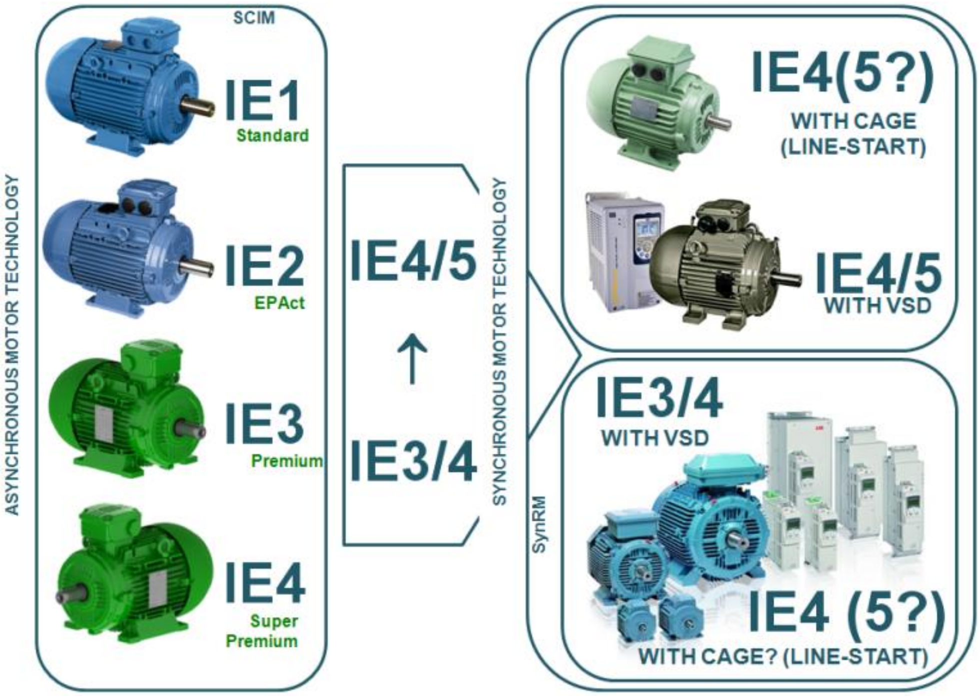

Figure 6 7 New energy-efficient motor technologies

Advances in motor design, tighter tolerances, the use of superior magnetic materials, larger copper/aluminium cross-section in the stator and rotor to reduce resistance are just some of the techniques that contribute to lowering the losses in induction motors and allowing them to reach very high (IE4) efficiency levels.

Other technologies, such as permanent magnet synchronous motors and synchronous reluctance motors, have been developed that also reach these high efficiency levels and are actually candidates to IE5 class.

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