New technology needs new policy - From component to systems

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Abstract

The electric motor market has witnessed a big change in the last decade: both in structure, with company mergers contributing to an even more global market, in content with energy-efficiency policies, and in its economy with rising costs of material and variable electricity prices moving the market towards more energy-efficient products.

Recent technological developments have led to the introduction of very efficient motors, often referred to as Super- and Ultra- Premium Efficiency Motors, with efficiencies well above the IE3 level [1]. Cost-effective induction motors (IM) with efficiencies on and above the IE4 threshold are now widely available on the market and other advanced technologies have enabled manufacturers to produce motors that exceed the IE4 and IE5[1] efficiency limits. Driven by the expanding market penetration of Variable Speed Drives (VFD), introducing big energy savings in motor systems with variable load, there is a growing concern over their efficiency, both in operation, in full and especially in part-load and also in stand-by mode. First evidence shows that significant differences exist between the efficiencies of VFD in the market with similar functionality. Developments in power semiconductor technology allow for a significant reduction in the VFD losses of up to 60%, as well as a reduction of the motor losses.

The largest part of the energy savings is made available by the optimization of the entire motor systems (20-30%) [2] [3]. But still to date, Minimum Energy Performance Standards (MEPS) have been targeted due to legal limitations mostly at individual components. Difficulties arise in the standardization of measuring and classifying the entire motor driven unit (MDU). The methodology to describe energy efficiency requires a new approach to take into account that different components are made by different manufacturers and need to be assessed together. The larger energy savings achievable together has stirred concerns from manufacturers of the increased burden of compliance with several individual MEPS for components (motor, VFD, pumps, etc.) is leading to the launch a combined system standard on IEC and ISO level.

The two approaches for standardization and MEPS, components vs MDUs, must be carefully complemented in order to achieve the maximum energy savings and carbon emission reduction possible. This needs to be achieved without imposing disproportionate burdens on both manufacturers and market surveillance which will discourage industrial users to acquire high performant systems.

This paper carries out technical, economic and environmental analyses of introducing new policy measures (standards and MEPS) for both individual components and MDUs.

[1] IEC 60034-30-1:2014 defines efficiency classes IE1 to IE3. The new class IE5 is not yet defined in detail but is envisaged for potential products in a future edition of the standard. It is the goal to reduce the losses of IE5 by some 20% relative to IE4.

Recent technological developments

Growing governmental and industrial awareness towards the importance of energy-efficiency and its benefits, together with the global diffusion of countries with MEPS, has led to the development of motors with very high efficiency, well above the IE3 level, often referred to as Super- and Ultra-Premium Efficiency Motors (IE4 and IE5, respectively). Induction motors with efficiencies on and above the IE4 threshold are now widely available on the market and other advanced technologies (e.g. permanent magnet motors, synchronous reluctance motors) have enabled manufacturers to produce motors that exceed the IE4 and IE5 efficiency limits.

For fixed speed applications, three-phase induction motors are still the best option because of their reliability, efficiency and cost. They represent today, by far, the vast majority of the market of electric motors both in sales and running stock. Several strategies can be used to increase the efficiency of induction motors: advances in motor design (namely thermal and winding design), tighter tolerances, the use of superior magnetic materials, larger copper/aluminum cross-section in the stator and rotor to reduce resistance, use of copper rotors 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 [4] [5]. Other technologies have surfaced capable of starting direct-on-line (DOL) such as Line-Start Permanent Magnet Motors (LSPM) and DOL Synchronous Reluctance (SR) motors, but they still present some operational challenges, such as the starting charateristics which hinder their wide spread use.

On the other hand, in variable speed applications Permanent Magnet Synchronous Motors (PMSM) and SynRel motors can present themselves as an alternative to induction motors, rivaling in reliability and excelling in efficiency. Since these motors operate at synchronous speed they do not have losses in the rotor and are, therefore, capable of achieving very high efficiency levels up to IE5.

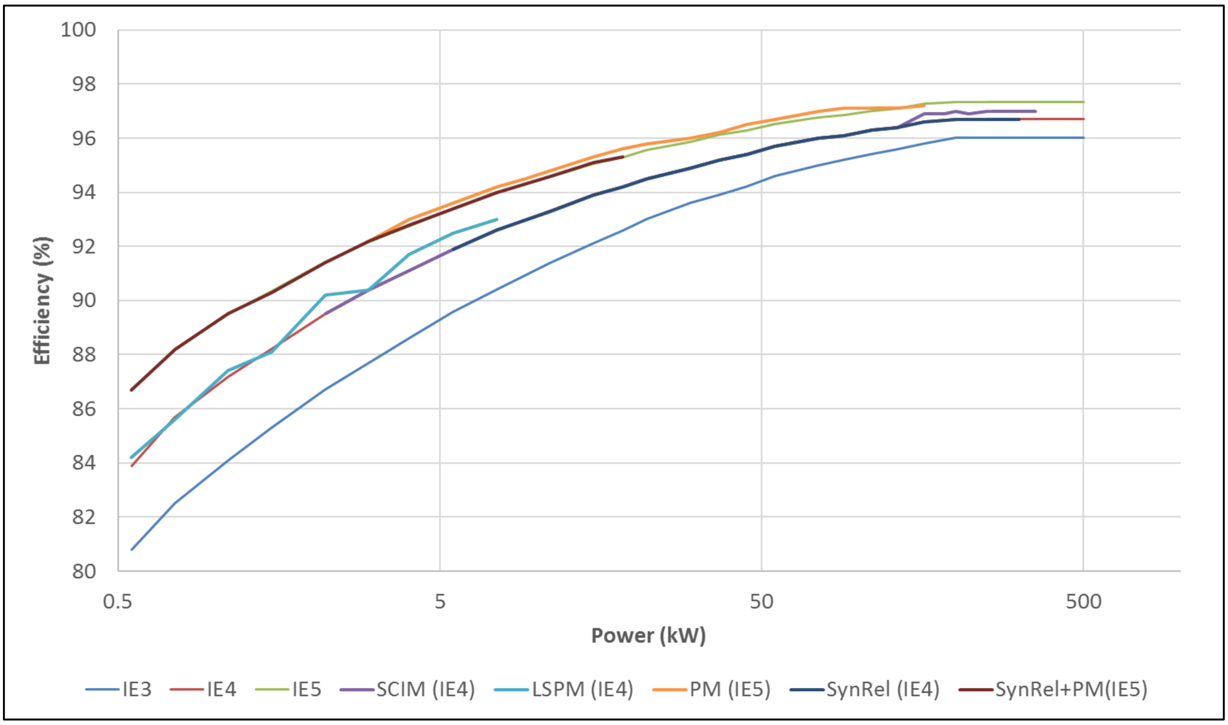

Figure 1 **Efficiency of commercially available IE4 and IE5 motors (Source: ISR-UC, 2016 catalogue data)**

The use of these technologies can also significantly reduce the overall weight and size of the motor meaning that less material is needed for its construction, including active materials.

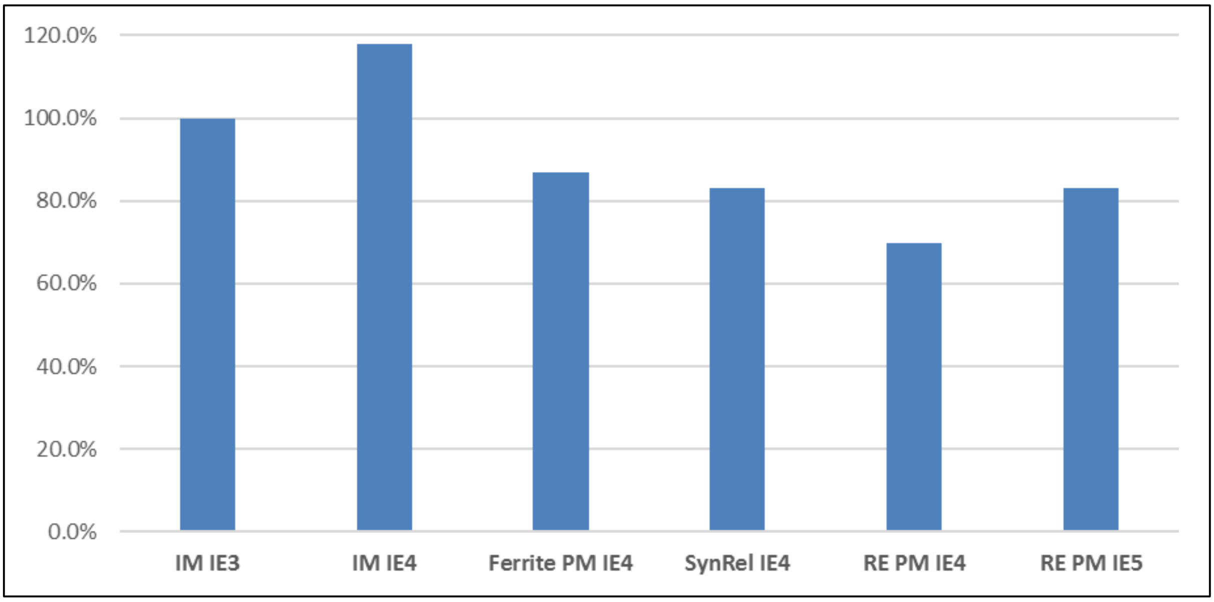

Figure 2 Relative Motor total weight (11 kW; 1500 rpm; aluminum frame; source: ISR-UC: catalogue data, 2016)

Because of the problems presented by the production of rare-earth alloy permanent magnets - (1) Price instability / uncertainty due to concentrated production of Rare Earths, (2) the limited supply of Dysprosium (Dy) and (3) the environmental impact of mining and refining these elements - some manufacturers have started production of motors using alternative technologies and materials, such as:

- Reduced-Dy magnet technology (e.g. Hitachi's dysprosium vapor deposition diffusion technology).
- Recycling (limited by economic feasibility).
- Development of new magnetic materials (some not yet commercially available): Iron Nitride, Samarium Iron Nitride, Cerium and Manganese-based compositions, magnetic nanoparticles and Iron Lithium Nitride [6].
- Much less costly and widely available Ferrite Magnets.

The increasing use of Variable Frequency Drives (VFD) for application with variable loads has also led to the increased awareness of its energy losses: in the VFD in operation, in standby and the further losses in the motor caused by non-sinoidal power supply. VFD 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 VFD.

Recent developments in power semiconductor technology and materials, such as GaN (Gallium Nitride) and SiC (Silicon Carbide), can reduce the losses in VFDs (both switching and conduction) by over 50% [7]. These technologies have had their cost decline due to their wider market penetration and economy-of-scale effects.

Another important contribution to the overall energy loss of VFDs is their standby and control power consumption which can also vary widely as can be seen in Figure 3. In IEC 61800-9-2, a standby and control loss of 50 W is included for all VFDs which makes for very low efficiencies in the small size segment of 0.12 kW and up to 2 kW.

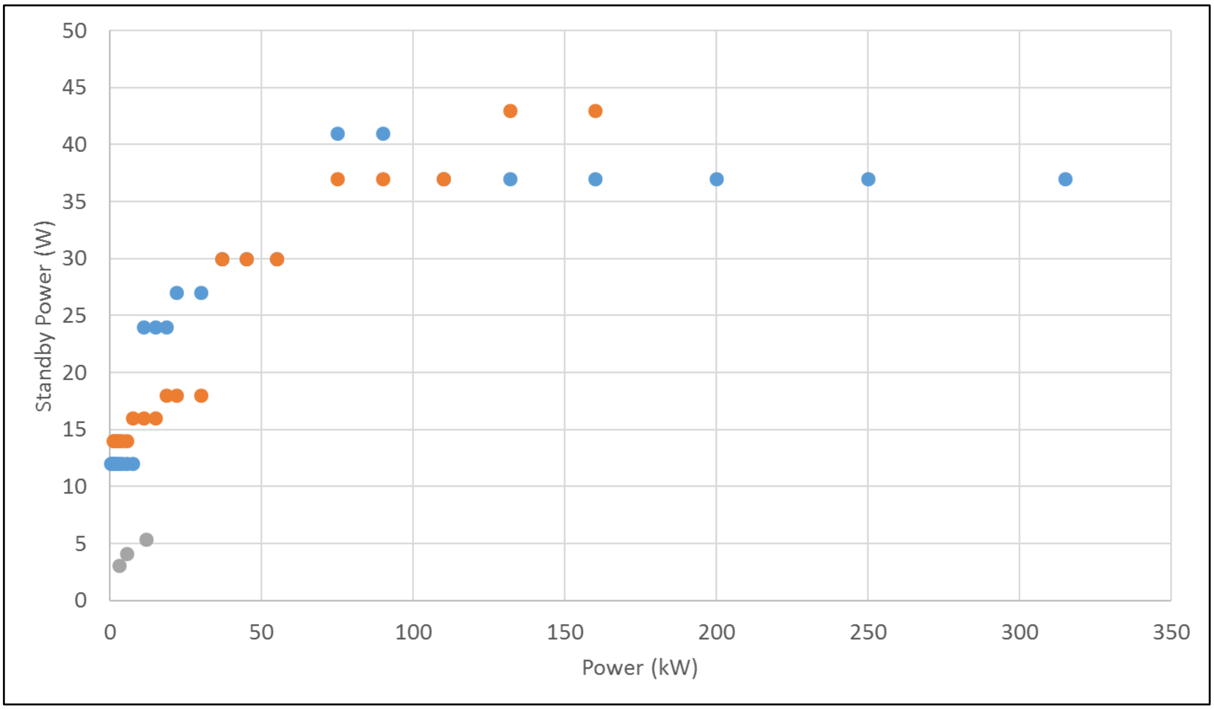

Figure 3 VFD Standby Losses (Source: ISR-UC, manufacturers' data, 2016)

Energy savings in Motor Driven Units

Savings from components

Motor systems (Figure 4) are made of individual components that work together to produce mechanical movement. Besides the motor there is the need for several groups of components: equipment for supplying it with power; optional electrical / electronic controls for starting and speed variation; components for mechanically transmitting motion to the driven equipment; the driven equipment itself; and optional mechanical controls and process components. Each of these parts of the system, when present, will have losses which when compounded determine the overall system efficiency.

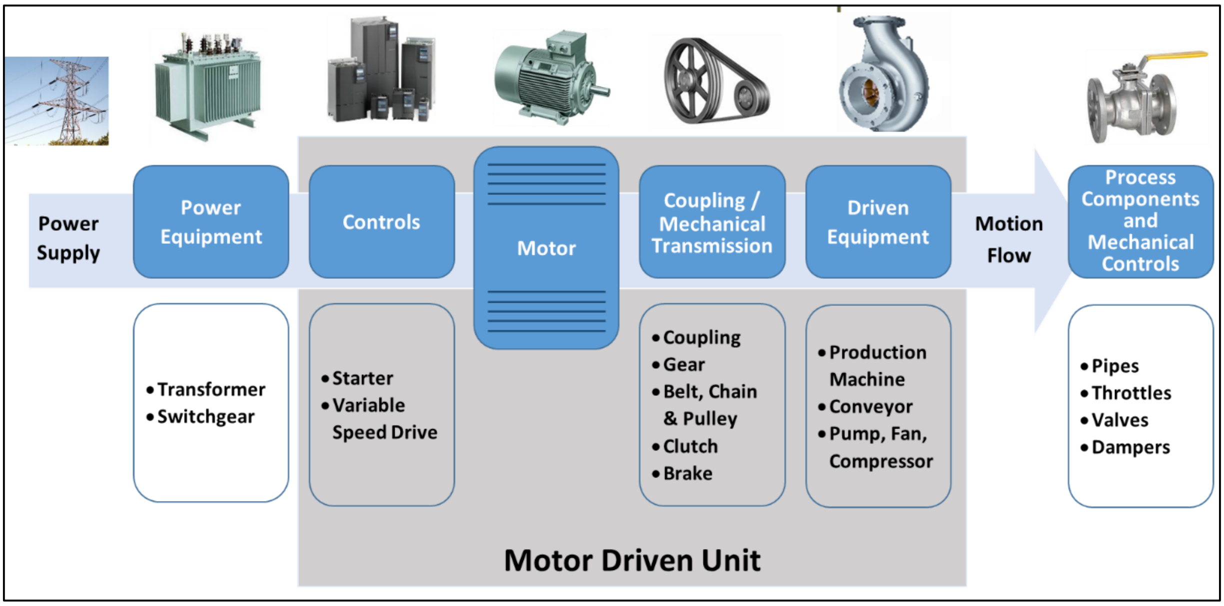

Figure 4 Example of motor system including Motor Driven Unit (Source: ISR-UC)

Savings from system integration

Although component efficiency is important, it is the total process control strategy which offers the highest energy savings potential. In the design of motor systems it is essential to precisely identify the mechanical load requirements (torque-speed characteristics) under a variety of operating conditions (e.g. starting/breaking, steady-state, variable load, on/off, etc.) and then ensure that the best control strategy is used to deliver over the entire operation cycle the desired torque and speed with the maximum efficiency.

In Figure 5, the main strategies to reduce the energy consumption in motor systems are depicted, namely, the reduction of power loss in the energy conversion process (motor & converter efficiency increase), reduction of motor & converter output power (reduction of load torque by means of process friction/loss reduction, counterweights use, output speed reduction, etc.), and re-use of stored kinetic and/or gravitational potential energy (energy regeneration for direct use in other motors & converters, injection into the mains grid and/or common DC bus, and/or energy storage in supercapacitors/batteries) [8] [9].

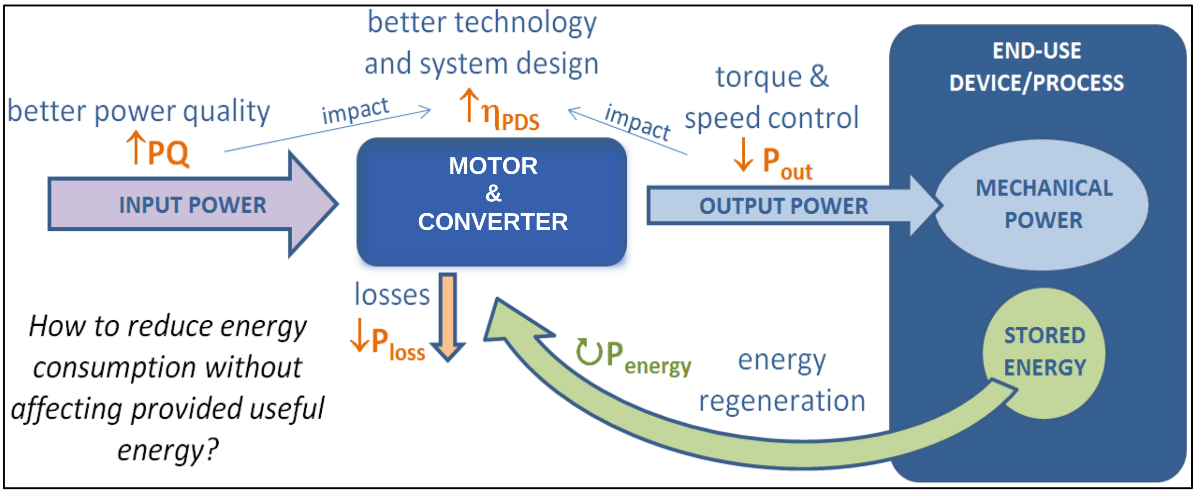

Figure 5 Strategies to reduce energy consumption in Electric Motor Systems (Source: ISR-UC, [8])

Optimized process control using sensors to closely match the output of the motor driven unit to the exact process needs (e.g. matching fan speed to the output temperature in a heat exchanger) as well as the use of regeneration can sometimes save a much larger amount of energy as using high-efficiency components. Loads with a high potential for regeneration include cranes, lifts, and traction/motion control.

Standardization and regulations for motor driven units

Standards

Motors

The International Electrotechnical Commission (IEC) with its 60034 standards series has set electric energy related international standards for low voltage motors (< 1 kV) between 0.12 kW and 1000 kW operated at 50 and 60 Hz. Both the testing standards and the efficiency classes are aligned and updated regularly. The process of harmonization of testing standards between IEC 60034-2-1, CSA 390 and IEEE 112 B has proven successful for fixed speed motors. The publication of the standard IEC 60034-30-1 [10] for harmonized efficiency classes (IE-code) in 2009 has been a global success story.

Lately, with the market success of variable speed applications and first proposals in 2009 [13], also converter fed motors are included in the testing procedure and efficiency classification. For a converter-fed motor a reference converter has to be defined because converters and motors are often not made by the same manufacturer. Agreement has been reached in IEC on the 7 relevant testing points with torque and speed (see Figure 6) as well as on the respective interpolation method [14]. With this, all potential operating points of the motor, the VFD and of the application can be easily calculated and verified by tests. But, the efficiency rating proposed for converter fed motors in IEC 60034-30-2 is so far based only on one single operating point: 90% speed and 100% torque of the motor. This does not allow to properly rate a converter with a motor in their typical field of part load operation.

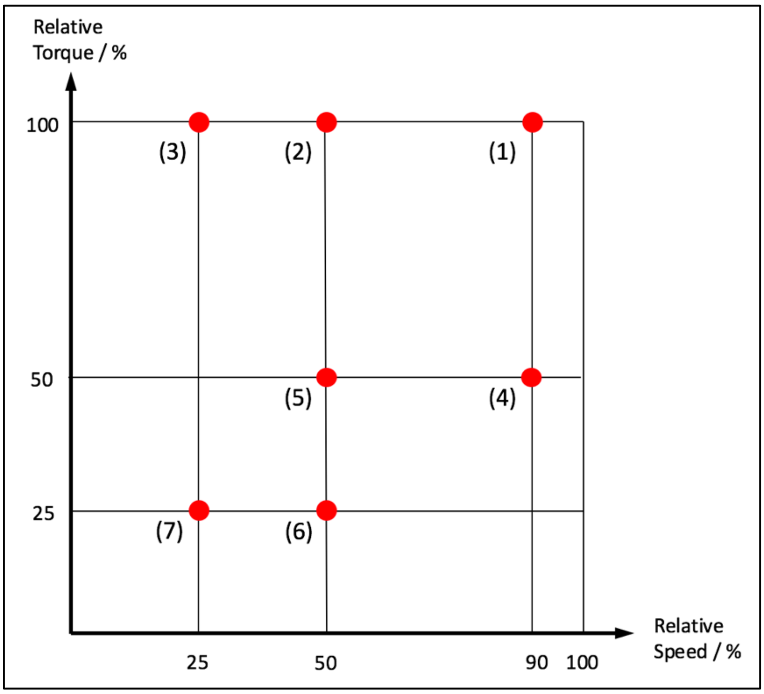

Figure 6 Standardized operating points (Source: IEC 60034-2-3 [15], draft edition 2, 2017)

Table 1 List of IEC energy relevant standards for rotating electrical machines [11]

IEC standard	Date of publi-cation, edition	Title
IEC 60034-1	2017 ed.13	Part 1: Rating and performance
IEC 60034-2-1	2014 ed. 2	Part 2-1: Standard methods for determining losses and efficiency from tests (excluding machines for traction vehicles)
IEC TS 60034-2-3*	2013 ed. 1	Part 2-3: Specific test methods for determining losses and efficiency of converter-fed AC induction motors, currently under revision
IEC 60034-30-1	2014 ed. 1	Part 30-1: Efficiency classes of line operated AC motors (IE-code)
IEC TS 60034-30-2*	2016 ed. 1	Part 30-2: Efficiency classes of variable speed AC motors (IE-code)

*) TS Technical Specification

The introduction of variable speed applications and new motor technologies (Permanent Magnet PM, Switched or Synchronous Reluctance SR) requires an update on testing procedures to include the necessary VFD and to rate the variable speed performance. This task has not yet been completed in IEC. It has launched a broad discussion on how the full and partial load losses in the VFD and the further losses in the motor have to be accounted for in the efficiency classification.

Another subject has not yet been dealt with are efficiency classes for Medium and High Voltage motors (above 1 kV). They are usually larger than 500 kW and are not made in large series. They tend to have slightly larger losses than LV motors but they do not need the respective voltage transformation and therefore do not have these transformation losses.

Variable frequency drives (VFD)

The introduction of variable speed operation with frequency converters changes the picture. The interaction of the VFD and the motors is complex. The advantages of converter use, especially in square torque applications (closed loop pumps, fans), is manifold. Extra losses of the converter at full and partial speed are not the only disadvantage. The motor itself suffers from the Pulse-Width-Modulation-induced non-sinoidal feeding and thus has a reduced efficiency.

The new IEC 61800-9 series is about to clarify standards for variable frequency drives. This means that both the testing standard and the efficiency classes for VFDs are be published in the same document. The testing standard is encountering some problems because the manufacturers of motors and VFDs are often not the same. This means that a "reference converter" has to be defined that will provide for repeatable and accurate efficiency test results. Earlier studies have shown that there are efficiency differences between products of different manufacturers. Therefore, an efficiency classification is necessary. Discussions with industry show that not all types and products of VFD can easily reach the predetermined testing condition. Also, the combined effect of a VFD and the motor are addressed. The current draft IEC standard has not been able to come up with a rating of efficiency at partial load which would be the critical operation point. The efficiency rating is done only in one point: at 90% speed and 100% torque of the motor. The ongoing revision for edition 2 might also reconsider the current analytical model which is based on an old analysis by one manufacturer. It is also desirable to agree that efficiency classes for motors, VFD and their combination are expressed as efficiency (input/output in %) and not only as an absolute loss (W) which is very difficult to compare.

Table 2 List of IEC energy relevant standards for adjustable speed electrical power drive systems [12]

IEC standard	Date of publication, edition	Title
IEC 61800-9-2	Published 2017, edition 1	Adjustable speed electrical power drive systems - Part 9-2: Ecodesign for power drive systems, motor starters, power electronics & their driven applications - Energy efficiency indicators for power drive systems and motor starters, publication expected in mid-2017. Revision (edition 2) has started

Motor Driven Units - the challenge for standardization

The integrated MDU has opened a new field for efficiency standards of mechanical performance of applications in pumps, fans, compressors that is dealt with by the International Organization for Standardization (ISO). Some small products (i.e. circulator pumps, exhaust fans, cooling compressors) include the motor, the application (pump, fan, compressor, etc.) and a VFD into one integrated package manufactured by one producer. This makes for easy testing and performance standards with the resulting efficiency equal to the mechanical output divided by the electrical input (%).

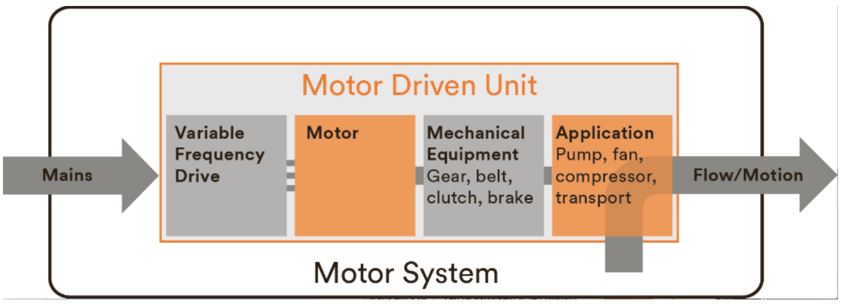

Figure 7 Definition of Motor System and Motor Driven Unit (Source: 4E EMSA 2013)

But, this integrated package is not the case in applications above 2 to 5 kW where the three components are often manufactured by two or even three different producers and assembled only on the factory floor. In such a case both the individual components, their interaction and the entire MDU have to be tested and eventually classified. This system efficiency η_{System} can be expressed in two different ways for the example of a pump MDU that lead to the same result:

$$\eta_{System} = \eta_{VFD} * \eta_{Motor} * \eta_{Pump}$$

or

$$\eta_{System} = (P_{Output} + \Sigma (P_{Loss\ VFD} + P_{Loss\ Motor} + P_{Loss\ Pump})) / P_{Input}$$

This calculation for the system efficiency does not yet solve the entire problem: usually the three major components are not independent, that means the addition of their losses does not return a complete result. As mentioned above, the VFD reduces the efficiency of the motor. This has to be accounted for by either an addition loss term or by a combined VFD-motor efficiency.

Table 3 List of selected energy relevant ISO standards for pumps, fans and compressors

ISO standard	Date of publication	Title
Pumps		
ISO 9906 ISO/ASME* 14414	2012 2015	Roto-dynamic pumps -- Hydraulic performance acceptance tests -- Grades 1, 2 and 3 Pump system energy assessment
Fans		
ISO 5801 ISO 12759	2007 2010	Industrial fans -- Performance testing using standardized airways Fans -- Efficiency classification for fans
Compressors		
ISO 1217 ISO 5389	2009 2005	Displacement compressors — Acceptance tests Turbo-compressors -- Performance test code

*) ASME American Society of Mechanical Engineers

The logical next step is to include motors and VFD together with the application in the performance standard, both for testing and efficiency classification. This needs a much closer cooperation between IEC in electrical and ISO in mechanical performance standards than the current attempts. This, and the fact that three major components are involved, increases the complexity of the MDU and makes standardization more complex.

In the IEC 61800-9-1 a first version of a possible methodology for MDUs that has been drafted (based on the earlier Cenelec standard EN 50598-1). It defines the relative power losses of the MDU in order to calculate the system energy efficiency for the whole application.

Table 4 New draft IEC standard for Motor Driven Units

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

Regulations

National regulations for industrial products, mainly for minimal performance requirements, are usually based on international standards where scope, metrics, methodologies of comparison of performance, efficiency tests, etc., are described in detail. Regulators are at ease when there is an established and widely accepted, globally harmonized standard as a base for a national regulation. Usually the regulation describes additionally only the scope, sets the Minimal Energy Performance Standard (MEPS) and the timeline of entering into force of the respective level of the requirements. It can also stipulate procedures of products (or systems) for check-testing, declaration and registration, etc.

In the three major industrial regions (China, Europe, USA) that in 2014 are responsible for 59% [16] of global electricity use for motor driven systems a fairly large number of component regulations for testing and efficiency classification of motors exist. A somehow shorter list exists for applications like pumps, fans and compressors. The list of countries that include advanced products and technologies (VFD, PM or SR motors) in their regulation is very short. The list of countries that also include regulations for entire MDUs (that are not small integrated and packaged units) is so far nonexistent because the respective IEC and ISO standards are not available yet.

The problem with energy performance requirements of MDUs is complex:

Currently the individual components of a MDU are regulated; the entire MDU is not regulated (with the exception of circulators in Europe and pumps in the US). This means that their interaction escapes the vigilance of the regulator. As we have seen above in the discussion of standards, the interaction includes some complexities in both the widely used partial load situation and the further losses in the motor when driven by a converter.

Industry obviously prefers the way small integrated and packaged products are tested and regulated ("wire to water", "wire to air", etc.) to be used also for larger assemblies: only output and input under rated load are measured in the laboratory, noted and checked. This makes assemblies of components impossible to be tested because they meet only on the factory floor. Physical performance testing in a factory is not possible as precisely as in a laboratory under controlled and repeatable conditions. Also, this leaves the field wide open to the industrial user to mix less performing together with higher performing components in order to meet a minimum requirement. This cannot be the goal of a regulator on the mid and long range.

In the European Ecodesign Directive the principle is included that a pump or a fan that is integrated into another product (like a washing machine or a refrigerator) has to comply with its respective MEPS also when the entire appliance has labels and MEPS to comply with. Industry has called this unnecessary burden "double regulation". Market studies in fans have shown that to exclude the fans built into other products a very large portion of products would never be checked and will remain on low efficiency levels.

Conclusions and recommendations

The challenge for standards in IEC and ISO

The hope is to eventually solve the problem of the large effort for testing and efficiency classification of MDUs by calculation and simulation. If the performance of an individual product and its interaction with another component in a MDU can be described in an easy way by a registered simulation program then the physical test would not be necessary anymore. This simulation needs to involve a series of coordinated standard operating points for a VFD (V, A, cos φ, harmonic content), a motor (torque and speed) and an application (for instance in a pump head and flow), a clear definition of the respective components and a weighted average of the performance at standardized operating points that fits both square and linear torque applications with different annual part load profiles. The simulation program needs to be verified by tests and calibrated according to a necessary international standard.

In the USA the Department of Energy has recognized the Alternate Efficiency Determination Method (AEDM) [18] for motors based on an accredited and third party verified simulation program. IEC is discussing whether an AEDM needs some special definition in any of the existing (or in a separate new) standards for motors. The subject has not yet been discussed as a simulation program for motors with converters and entire MDUs.

The challenge for regulators

Regulators need to consider that on one hand they want to have a transparent market moving unhindered towards more efficient components and MDUs. On the other hand they cannot impose check testing and registration programs without considering the burden and cost for manufacturers in testing, labeling and compliance documentation and certification. The IEC System of Conformity Assessment Schemes for Electrotechnical Equipment and Components (IECEE) as a certification program [19] for motors is certainly a first move in the right direction.

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