Design of electric motors and power transmission systems according to performance standards

Mr. Prakash .K. MUTAGI
Lecturer(Senior scale)
Department of Electrical & Electronics Engg.,
Government Polytechnic, Karwar

Mr. Chandrakant. P. Tupale
Lecturer
Department of Electrical & Electronics Engg.
Government Polytechnic, Zalaki

Abstract:
This article focuses on high design efficient electric motors introduced in power transmission systems. Final performance standards are considered limitations for engine and drive design: they are introduced and described and their influence on the choice made during the design process is emphasized. As a special case the engine manufacturer's perspective is presented sequentially understand what the right level of efficiency is engine that meets performance requirements transmission system It is not always clear and simple understand because the two have different standards contexts An example of a design of an industrial engine with a power of 3 kW power is included which also shows test results a prototypes Also the standards related to the exam tests, especially those that determine the accuracy of the instrument, discussed and commented on in the magazine.

Keywords: —High efficiency motors, Energy Saving, Efficiency classes, Power Drive System, Complete Drive Module, Electric Motor

1. INTRODUCTION

Much work has been done to improve this in recent years human energy efficiency and carbon dioxide reduction emissions in the future. Among other things, it's worth it mention the Kyoto Protocol, the signature of which obliges the European Union to achieve the so-called 20-20-20 goal by 2020. The implementation of such goals is one of the most important means .The EU has adopted the Energy Related Products (ErP) Directive. 2009/125/EC [1]. The ErP Directive, also called Europe .The Ecodesign Directive establishes a minimum level of energy efficiency requirements for manufactured or imported products European Union. It also requires that all products electricity consumers are rated for energy presentation This category also includes electric discs and as a result, many standards and regulations apply the product's effectiveness claim has been published. The European standard EN 50598-2 [2] defines the procedure and test results must be considered when determining energy class and losses of electronic converters and frequency converters for voltage up to 1000 V and nominal power 1 MW. The efficiency class is determined by comparing losses with a real system with an ideal reference system. The standard EN 50598-2 has been replaced by the standard IEC 61800-9-2 [3] on eco-design for energy use systems, power electronics and their controlled applications. Two other documents complete the standard framework: IEC 61800-9-1 for applications other than electricity frequency converters and EN 50598-3 which defines the procedures to be used to determine the environmental product description. In the year several policy and implementation studies in recent years [4]–[6] are based on these standards. Another important regulatory group, viz. 60034-30- 1, 60034-2-1 and 60034-30-2 [7]–[9], specify procedures determine losses and efficiency class electric motors. Standard 60034-30-1 defines performance classes for grid sine input, while 60034- 30-2 consider using an inverter. IEC 60034-2-1 the standard defines specific test methods and

instruments requirements for testing electrical machines. Standard IEC 60034-2-3 [10], recently updated, specifies test methods and determine the losses and efficiency of the interpolation procedure of transformer operated motors. Both synchronous and inductive machinery is covered and the engine is considered a part variable frequency transmission system PDS. Electric motors strictly comply with the EU regulation 1781/2019 [11], which repeals directive EU 640/2009 [12]. This standard set the following schedule for minimum energy efficiency Requirements for electric motors: from 01.07.2021 energy efficiency of three-phase motors with a rated power of 0.75 kW to 1000 kW meets at least IE3 level of efficiency. From July 1, 2023, energy efficiency three-phase motors with equal or greater rated power 75 kW and at least 200 kW at least IE4 performance level. There are special recipes intended for engines intended for special use, such as explosion-proof motors, single-phase and other low-power motors. The novelty brought by the EU 1781/2019 regulation is also establishing a minimum performance requirement operation with the rotational speed of the engines, i.e. the inverter: 1 Power losses of frequency converters operating in July 2021 engines with a nominal power of at least 0.12 kW and equal 1000 kW or less must be of efficiency class IE2. In addition to the regulations on the electric motor and drive devices, too standards related to a specific product are of great interest. For example, companies that provide components, kit fans or integrating electric motors and fans in it the products must meet the requirements set by them ErP Directive. In fact, it affects both the motor and the fan according to the law. Implementation of the ErP Directive for the ventilation industry complies with the EU regulation 327/2011 [13] on the ecological design of fans with electric motors with an input power of 125-500 kW, its extension 1253/2014 and EU regulation 1781/2019 [11] on electric motors. The rules dictate minimum performance levels, such as general performance levels fan, motor and operating system are achieved. Similarly standards are also developed for other areas, e.g how to pump water Considering a complex system such as a fan or a pump, it is not trivial to find out what the efficiency is required for each individual component, ie. frequency converter, motor and an impeller to meet the requirements end product standard. This is especially important when the system is composed of products from different manufacturers manufacturers Many studies deal with this topic damage assessment in electrical machine and power converter, also taking into account the effect of powerful electronic current and/or voltage distortions on the electrical machine [14] - [22]. The possibility of increasing the efficiency of electricity engines, especially for those industrial applications where Squirrel cage asynchronous motors (IM) are widely used, many different solutions have been proposed. For example, stator and rotor geometry optimization, exchange aluminum with copper in the rotor cage or replacement with IM Synchronous motors.

Synchronous motors are most popular candidates for higher efficiency engines because they do not suffers from rotor losses. Among the various possible rotor configurations of a synchronous machine is a permanent magnet (PM) assisted synchronous reluctance machine appears to be the most promising because it combines PM configuration and using the reluctance moment [23]–[25]. However, such a machine assembly involves a number of critical considerations must be carefully considered during the design phase of the frequency converter. Impedances to rotor current must be properly designed so that they avoid torque ripple. In addition, the engine parameters are displayed a strong non-linear property that can lead to complexity when driving the engine, especially if there is a dull operation wanted. In addition, other factors make switching difficult of existing engines with high-efficiency engines e.g environmental impacts of the new motor industry and/or necessary financial investments. Production Building new engines can require constant energy and materials, resulting in negligible environmental impact. There are some solutions to these problems have been proposed, for example without tool costs or effective rework strategies [26], [27]. This article presents a detailed performance evaluation of a low power electric drives with a power of 0.18 kW - 15 kW, which are typical for industrial applications. The this application addresses a number of mandatory standards and comparative analysis of different specifications performance levels are provided. Especially from a point of view the engine manufacturer is used to understanding what is the correct efficiency of the engine to meet the performance requirements of the power transmission system [28]. As a special case study, the design is 3 kW high powerful engine is introduced. The design is optimized rated power and then find out how efficiency class of both engine and PDS (where engine is introduced) changes the scale of the design to match other power classes with the same geometry. Approved design procedure was verified and confirmed an experimental test with a real engine. The measurements are also included the prototype and engine design were exported meet energy efficiency standards.

2.REVIEW OF STANDARDS AND REGULATIONS DEFINITION AND CALCULATION OF EFFICIENCY CLASS

There are several standards and regulations related to this defining the efficiency class, its determination and measurement This section provides an overview of the actual taking into account European IEC standards in particular. The The most important standards are: IEC 61800-9-2 [3] which is valid eco-design of power transmission systems, power electronics and the applications they control; 60034 standard group [7]– [10], which define the efficiency classes of electric motors and related testing procedures. In particular, the IEC standard 60034-2-3 [10] defines test methods for determining losses and performance, including requirements for instrumentation, for transformer-fed AC motors that include both induction and synchronous machines. In addition to IEC standards, IEEE has published a guide to testing permanent magnet machines [29]. The focus is not only on efficiency, but also on the overall vision Methods of testing synchronous machines are given. In addition to these standards, some others are more specific settings dedicated to a specific application could apply. For example, a special ventilation standard systems and pumps are currently under development. This last one however, the case is beyond the scope of this paper and is not present included in the following discussion.

A. Regulation for power drive system IEC 61800-9-2

Fig 1 shows the expanded product layout as seen in standard IEC 61800-9-2. Includes electric drive, load and other components included in the application such as mechanical joints, belts or gearboxes. The same system component nomenclature is used here paper The standard contains performance class definitions for the transmission system and PDS; and the whole ride module (CDM). PDS consists of CDM and electric motor, including the feeding part and auxiliary equipment. For example, wires, switches and fuses is considered when it comes to nutrition. Arrival and departure CDM filters are considered in the auxiliary equipment.

1) Calculation of IES Degree for PDS manufacturers: This section describes the definition of performance class as a whole PDS is available. This applies to PDS producers produces both the CDM and the engine.Definition the efficiency class is based on the calculation of losses system Fig 2 shows the flow chart of the procedure Calculation of PDS efficiency class according to the standard. Capitalization according to standard nomenclature P stands for absolute losses and lowercase p refers relative losses. In addition, the working point is determined when suitable For example, pL,RPDS(90;100) are relative losses etalon-PDS 90% of rated speed and 100% of rated speed torque.

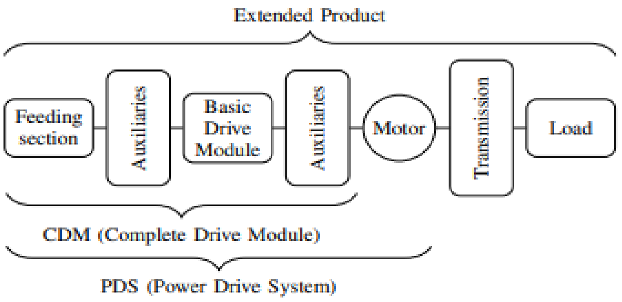

Fig. 1. Extended product overview as defined by IEC 61800-9-2 [3]. The CDM consists of the variable voltage and frequency power converter. The PDS includes the CDM and the electric motor. Finally, the extended product include also the load and the transmission (such as the fan or pump plus the mechanical coupling that could include belt or gearbox).

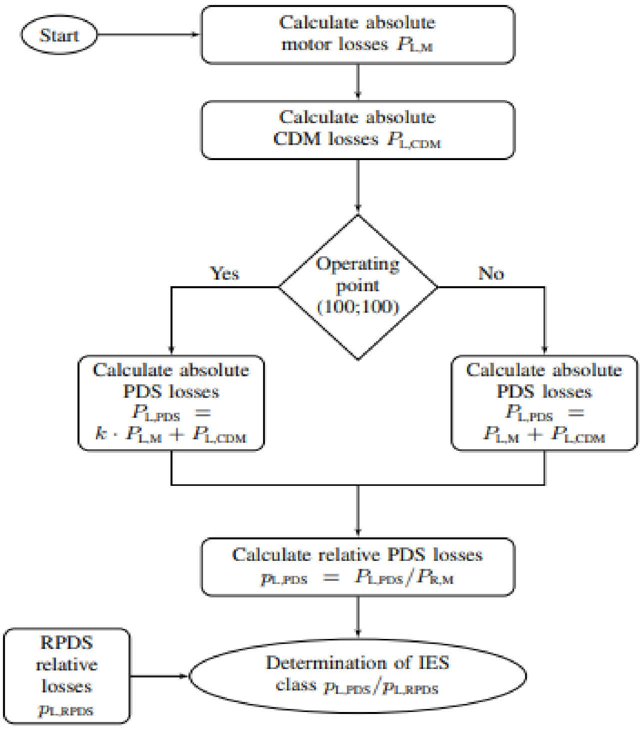

Fig. 2. Procedure to compute the IES class for PDS as specified in standard IEC 61800-9-2 [3].

The process begins with the calculation of actual damages PL,M and CDM PL,CDM actual losses of the engine. The

PDS relative losses pL,PDS are then calculated also considering special work areas. Finally, the efficiency class of the PDS is calculated Comparison of PDS relative losses with losses defined by pL,PDS with the same performance in the reference system standard pL,RPDS, i.e. considering the ratio pL,PDS/pL,RPDS. Because IES class definition, the standard defines the operation at 100% of rated torque and 100% of rated speed. Three IES performance classes are defined for PDS:

- IES1 class if pL,PDS are within ±20 % of pL,RPDS;
- IES0 class if pL,PDS are at least 20 % higher than pL,RPDS;
- IES2 class if pL,PDS are at least 20 % lower than pL,RPDS.

Overmodulation at nominal voltage when using CDM a problem may arise, and in the worst case an impossibility run the engine at rated speed. To avoid this The problem is that RCDM losses are given at 90% of the nominal value engine speed (ie pL,RCDM(90;100) is enabled). It can be assumed that the CDM losses are 90% of the rated speed same as in nominal use. As for the electric motor of CDM that cannot provide rated base voltage at rated speed, it is open higher losses due to increased motor current. Therefore in Engine losses are given to solve this problem at rated speed and torque, ie. pL,RM(100;100), increases factor k as shown in the Fig. 2. As in the passage standard, assuming a CDM voltage drop of 10%. losses are expected to increase by 11%. In this case, this it follows that k = 1.11.

2) IES class calculation for engine manufacturers: an important situation prescribed by the standard is possible calculate IES grade for PDS if it is only part components are available. This is for example engine manufacturer who wants to predict the IES class of PDS applied with electric motors. In this case, they an IES class can be assigned assuming the engine is used CDM, which refers to the loss specifications in its technical data. Another situation is when there is no CDM defined this is how the engine should be for the final PDS used in conjunction with RCDM with losses defined in the standard IEC 61800-9-2. As detailed in the flowchart in Fig. 2 if the engine is lost is given at an estimated speed, as is usually the case on data sheets the coefficient k is used to correct motor losses. The resulting relative PDS losses are calculated as follows:

$$p_{\mathrm{L,PDS}(100;100)} = \frac{P_{\mathrm{L,CDM}(90;100)} + k \cdot P_{\mathrm{L,M}(100;100)}}{P_{\mathrm{r,M}}} \qquad (1)$$

where PL,CDM(90;100) are the CDM losses, Pr,M is the motor mechanical power and PL,M(100;100) are the motor losses which have been corrected with k. Then the efficiency class of the PDS is obtained as previously described considering the ratio pL,PDS/pL,RPDS. A similar approach can be adopted also to compute IES class when only the CDM system is available, i.e. using the data of a reference motor defined in the standard.

B. Regulation for electric motors IEC 60034-30-2

Standard IEC 60034-30-2 defines IE efficiency classes from engines to variable applications so in this case the motors are considered as the energy source of the frequency converter. This standard defines five classes (IE-1 to IE-5). the efficiency depends on the rated power and rated speed of the motor. The engine efficiency must be included in the IE class definition measured at 100% rated torque and 90% rated speed, thus, the efficiency at n90 is denoted as η90. Because converters are the goal voltage drop, the test requirement for n90 motors ensures that the motor is operating at maximum magnetic flux avoiding overmodulation. To account for the reduced efficiency of the engine operating at partial speed, correction factor rHL osses are introduced. It is 0.15 for engines up to 90 kW. In addition to the fractional reduction in efficiency, the coefficient rHL also takes into account the resulting additional losses inverter modulation.

Table I

COMPARISON OF REGULATIONS ON INSTRUMENTS ACCURACY FOR THE MEASUREMENT OF PDSS AND ELECTRIC MOTORS.

	IEC 61800-9-2	IEC 60034-2-3
Power Analyser	• 0.2 % of the CDM apparent power (at 50/60 Hz)	• 0.2 % of the electric motor apparent power (at 50/60 Hz) • 0.3 % of the electric motor apparent power (up to 10 times f_{sw})
Torque Meter	• 0.2 % of the full scale	• 0.2 % of the full scale (if η lower than 92 %) • 0.1 % of the full scale (if η lower than 95 %) • 0.05 % of the full scale (if η higher than 95 %)
Frequency Measure	• 0.1 % of the full scale	• 0.1 % of the full scale
Speed Measure	• resolution of 0.1 rpm or better	• resolution of 0.1 rpm or better (for speed up to 3000 rpm) • 0.03 % of the full scale (for speed above 3000 rpm)

C. Regulation on test methods

Introduction of advanced performance classes to international standards, also has a significant impact accuracy requirements of instruments used in measurements. Higher efficiency, actually lower losses for measurement and thus a more accurate measuring device is necessary It is also characterized by higher efficiency classes due to smaller loss differences. Among the various efficiencies described measurement methods, the most recommended is the input method, where the efficiency is calculated by the ratio output and input power. Or for electric motor and PDS measurements output power Pout is the calculated mechanical power mechanical torque Tm and mechanical speed nm, both measured from the motor shaft. The input power of the PDS corresponds to the electrical power On the online side of CDM. Such power is usually present network frequency .If the efficiency of the electric motor is estimated input power is calculated at the output of the device CDM. The two power measurements are quite different the CDM output is usually variable frequency PWM waveform The complexity of high frequency measurement the harmonic spectrum generated by the inverter is significant and has in device management. On the tab. The equipment requirements defined in the standards are provided by comparing the PDS measurement requirements (standard IEC 61800-9-2) with them.For electric motors (IEC 60034-2-3). It is clearly noticeable stricter requirements established in the standard IEC 60034-2-3. In particular, a power meter must be provided accurate measurement of the additional losses incurred inverse modulation. Therefore, the power meter should be accuracy is 0.3% or better at least 10 times switching frequency fsw. In addition, 50/60 Hz the accuracy requirement is 0.2%. It should be noted that in IEC 60034-2-3 power meter accuracy is given at 50/60 Hz even the rated frequency of the included electric motor ride may vary. Regarding the measurement of electric motor torque, IEC 60034-2-3 introduces the increased precision requirement of high-performance engines. in according to the wider mechanical speed range allowed standard IEC 60034-2-3 for reversible motors sets a less restrictive accuracy requirement of 0.03% a speed measurement above 3000 rpm.

When testing electric motors IEC 60034-2- 3 reports that the converter configuration requirements are OK determine the prerequisites for reproducible test conditions. The the main limitation of inverter switching frequency which must be less than 5 kHz for higher speed motors up to 3600 rpm or below 10 kHz if the rated speed is higher 3600 rpm.

Table II
REFERENCE VALUE FROM IEC 61800-9-2 FOR A 3.0 kW RATED POWER MOTOR.

RCDM (90;100)			RM (100;100)			RPDS (100;100)		
$S_{r,equ}$	kVA	4.44	P_{rM}	kW	3.0	P_{rM}	kW	3.0
p_L	%	6.72	p_L	%	19.5	p_L	%	31.59
P_L	W	298.37	P_L	W	585.0	P_L	W	947.7
η	%	92.32	η	%	83.68	η	%	75.99

3. EFFICIENCY REQUIREMENTS FOR A 3.0 KW POWER DRIVE SYSTEM

In this Section the efficiency constraints and definitions described in the previous Section are applied to a motor drive with 3.0 kW rated power and 3000 rpm rated speed. The considered drive is adopted in ventilation system for industrial applications.

A. IES class computation for the whole PDS

There must be actual PDS losses to define an IES class compared to RPDS. Table. II indicates the standard technical data of the motor drive system considered. in particular, the relative losses pL of all RCDMs are reported, RM and RPDS. The table also shows absolute losses reported calculated as PL = pL ·Pr,M for RM and RPDS, and if PL = pL · Sr,equ for RCDM, where Sr,equ is the output Apparent power of CDM. The RM and RPDS efficiencies are then calculated as follows:

$$\eta = \frac{P_{r,M}}{P_{r,M} + P_L} \quad (2)$$

Table III
IE-1 TO IE-5 CLASS MOTORS AND PDSS LOSSES. FOR A 3.0 kW RATED POWER MOTOR AND 2500 RPM.

	η_{ref}[%]	$P_{L,ref}$ [W]	$k \cdot P_{L,ref}$ [W]	$P_{L,PDS}$ [W]
IE1	81.5	680.98	755.89	979.7
IE2	84.6	546.10	606.17	829.9
IE3	87.1	444.32	493.19	717.0
IE4	89.1	367.00	407.37	631.1
IE5	91.1	293.08	325.32	549.1

As far as the efficiency computation for the RCDM is concerned, it requires to know the active output power of the RCDM (Pr,CDM) that is not provided by the standard. Anyway, knowing RM mechanical power and its losses, the active power of RCDM can be assumed as:

$$P_{r,CDM} = P_{r,M} + P_{L,RM} \quad (3)$$

and then RCDM efficiency computed as:

$$\eta = \frac{P_{r,CDM}}{P_{r,CDM} + P_{L,RCDM}} \quad (4)$$

B. IES class computation using a RCDM

This section describes the calculation of IES efficiency category for PDS when only the engine is considered. Some general considerations for the procedure presented here are given in Section II-A2. according to the EU regulation 1781/2019, the CDM must meet the efficiency class IE2. Since CDM is not available, electrical losses are included regulation is confirmed, i.e. 25 percent lower than RCDM. Therefore, from Tab. II, the accepted CDM losses are PCDM = 0.75 · PRCDM = 223.78 W. Since these are CDM losses specified by the standard, The final IES performance rating for PDS depends actual engine efficiency. Generalize and in for general information useful for planning different performance categories are considered. in specifically all five classes from IE-1 to IE-5 as reported According to IEC 60034-30-2, actual losses are considered is calculated as follows:

$$P_{L,ref} = P_{r,M}\left(\frac{1}{\eta_{ref}} - 1\right) \quad (5)$$

Actual losses are required to calculate the IES PDS efficiency class and values are presented in the Table. III. for for completeness, also damages caused by repairs factor k is presented according to the flow diagram in Fig 2. The last column of the table shows the resulting PDS losses, calculated as the sum of all motor loss and RCDM losses, i.e. PL,PDS = k · PL,reference PL,RCDM. Fig 3 shows the same results as Tab. III, emphasizing part of the total losses of different parts of the system. Clearly lower engine efficiency, higher total loss of PDS. The horizontal lines indicate the loss levels used in the standard for defining efficiency classes. Comparing bars and horizontal lines makes this easy to evaluate the PDS performance class. For example, if an IE1 engine is approved, PDS is clearly IES1 performance class Similar considerations apply if IE3, IE4 or The IE5 engine is implemented, which in this case is clearly inside the PDS IES2 performance class. With the IE2 engine, the situation is forced to estimate more precisely, because PDS could be either IES1 or IES2 efficiency class according to specific losses of the engine. However, according to the schedule According to EU regulation 1781/2019, PDS must comply with IES2 level of efficiency.

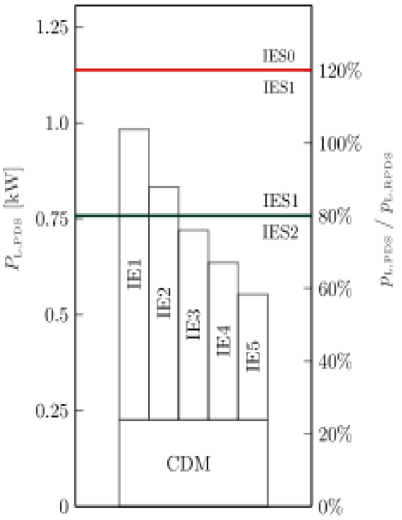

Fig. 3. Losses of a 3 kW mechanical power PDS. CDM losses are estimated using the reference given by the standard. Motor losses are the corresponding losses for motor in IE-1...5 class. PDS class thresholds are reported.

C. Extension of the motor power range

The approach presented in the previous section was extended to consider the power from 0.18 kW to 15 kW. Normalized power ratings in IEC 60034-30-2 and in IEC 61800-9-2 is included in the analysis. Such power there are many practical household appliances to choose from equipment for industrial applications. Fig 4 shows the losses calculation of all power classes, also emphasizing PDS performance classes. To improve readability results are presented as the ratio pL,PDS/pL,RPDS. It also allows observing the behavior of the efficiency demands change the rated capacity of the PDS. Information approximately 3.0 kW PDS, is the same as in Fig 3. It is interesting to observe how the limit changes moving to higher power levels. because of me IES2 grade PDS is obtained using IE3, IE4 or the IE5 engine. As power increases, IES2 class PDS can be implemented with either the IE2 engine.

4. MOTOR DESIGN OPTIMIZATION FOR A SPECIFIC EFFICIENCY CLASS

This section discusses the design of the engine according to specific requirements performance class requirements. The engine is assumed to be running when using adjustable speed for centrifugal machines such as e.g ventilation and pumping systems. In such applications nominal data are not always limited standard values and different applications may require slightly different power. Therefore, the engine structure must be rearranged to achieve the specified power and speed given efficiency class. Of course, the engine assembly ie. lamination geometry and winding configuration must be confirmed for higher powers that are close enough. This clearly limit production costs. The procedure is described considering an engine with a power about 3 kW. Same engine geometry use in all engines around them a value that controls the length and number of turns of the stack.

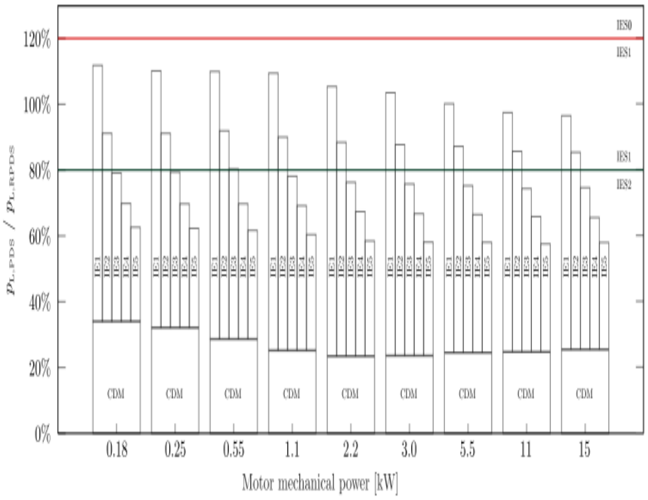

Fig. 4. Percent PDS losses relative to reference PDS losses, for different mechanical rating powers. CDM losses are estimated using the reference given by the standard. Motor losses are the corresponding losses for motor in IE-1...5 class. PDS class thresholds are reported.

A. Design of the motor configuration

The starting point for engine design is the existing IM with a nominal power of 3 kW with frame size IEC 80 [30]. The engine manufacturer sets additional restrictions: The same frame size and stator lamination must be used for the new model. Also the number of bars and the winding the configuration cannot be changed to limit production costs. The torque profile must be flat to limit system vibration and noise. Additional requirements are also defined for the frequency converter, in particular, the engine must work with sensor and sensorless control. In addition, the engine can be supplied as a part PDS is sold directly by the manufacturer or as an engine with customers with third party inverters. Considering given limits, internal permanent magnet (IPM) the assembly is selected for the new model rotor. Therefore, only the rotor geometry is provided Optimization techniques: 2D finite element simulations are used to carefully evaluate the design and achieve the best candidate [22], [32]. To identify the best configuration to meet the aforementioned constraints, the optimization objectives are maximum efficiency at nominal value operation and minimum torque ripple. Fig 5 shows a sketch as rotor geometry optimization variables considered in relation to design optimization. They are the air gap thickness g considered non-uniform based on thickness Δg to reduce torque and improve torque back EMF harmonic spectra; magnetic thickness etc and polar angle ϑp. The optimization is based on a differential evolution algorithm combined with finite element simulations. In addition Fig 5 shows the number of rotors, other optimization variables was stator current density, PM thickness and stack length As a limitation, the minimum air gap was set to 0.3 mm, maximum pile length 100 mm and max current density 7 A/mm2 RMS. For PM thickness, based on this, a minimum value of 3 mm was established demagnetization requirements. Fig 6 shows the target level obtained by optimization. The efficiency is calculated based on the rated power operation Individual engines are compared in the same way name electromagnetic torque. Worth noting a significant reduction in torque ripple reported as a percentage of the rated torque. Chosen person target country located at 93.1% efficiency and 4.8% of a torque ripple. If rotor lamination is selected, it is possible to define a motor configuration, i.e. certain stack length Lstk to meet exact performance requirements in the engine or PDS as described in Chapter IV-C and subpart IV-D. Precisely for this purpose an effective model of the actual design of the machine is mandatory. Such a model is described in the next section.

B. Efficiency determination model

Since the same motor configuration is used for tuning nominal power of the PDS, it is important to have motor efficiency calculation model for different batteries length. This is achieved by combining the finite element results simulation with analytical model of the proportional motor results with actual machine length. To increase To ensure the accuracy of the model, specific tests were carried out to carefully evaluate the mechanical losses of the motor. As if carefully check bearing characteristics and wind losses and Specific data has been provided by the engine manufacturer.For a given speed, the unit length (Lstk) of the motor simulated by FE simulation method taking into account different factors supply current, to find out electromagnetic energy P.AEF EM, maybe. An appropriate current range has been considered based on to the thermal limit of the motor.In the following, the index pu refers to the given quantity for the unit stack length and the exponent F EA represents The quantity is calculated using finite element analysis.Other quantities are determined by analytical methods as described in next. Once P AEF EM,pu calculated, nominal mechanical value PM power for a particular Lstk is calculated as follows:

$$\begin{aligned} P_{\mathrm{M}} = P^{\mathrm{FEA}}_{\mathrm{EM,pu}} \cdot L_{\mathrm{stk}} - P^{FEA}_{\mathrm{Lfe,pu}} \cdot L_{\mathrm{stk}} \cdot K_{\mathrm{HL}} - \\ P_{\mathrm{Lwi,pu}} \cdot L_{\mathrm{stk}} - P_{\mathrm{Lbr}} - P_{\mathrm{Lfan}} \end{aligned} \qquad (6)$$

where iron losses P F EA Lfe,pu and mechanical losses are considered. The latter component is divided into airgap windage losses PLwi,pu, bearing losses PLbr and self-ventilation fan losses PLfan. Such losses components are computed from experimental tests available on many IM available by the motor manufacturer. On the other side, the electric input power PE to the motor is computed as:

$$P_E = P^{FEA}_{EM,pu} \cdot L_{stk} + P_{LJ,pu} \cdot L_{stk} \cdot K_{HL} + P_{LJew} \cdot K_{HL} \qquad (7)$$

where PLJ,pu represent the Joule losses of the in-slot winding in pu, and PLJew are the Joule losses in the end-winding part. Moreover, the motor is subject to additional losses introduced by the CDM high frequency modulation. These additional losses are considered by the coefficient KHL in both iron losses and Joule losses. According to the standard IEC 61800-9-2, its value is set to 1.15. A prototype of the new engine has been built and tested to confirm the design. Fig 7 shows the test image benches are used for the test. Fig 8 shows the comparison between experimental results and engine calculations effective for various loads, including overload operation. The temperature variation of the coil with different loads has were included in the analysis. Operating at rated speed of is considered. Efficiency measurements made standard as stated in seconds. II-C. IN specific tool tailored to measure IE5 . performance The engine has been adopted. The motor has also been tested at the recommended partial load by standard. Works at different torques and speeds the values are copied on the test bench. Fig 9 shows comparison between experimental measurement (M) and calculated with the described efficiency model (C). Very Good agreement can be observed for mean and nominal loads. There is a larger deviation in the predicted performance value at very low loads. However, this has no effect on the ability of the model to predict the effective class accurately for PDS.

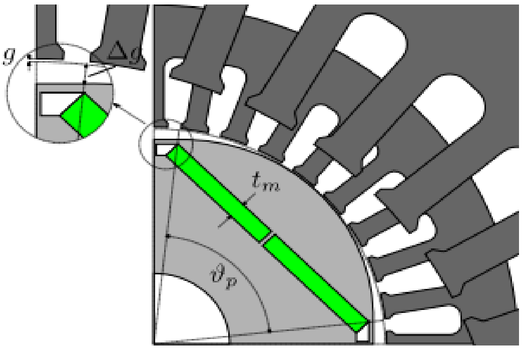

Fig. 5. Geometry of the IPM motor designed with the variables considered during the optimization.

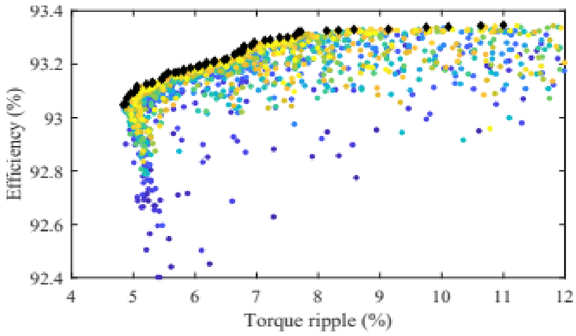

Fig. 6. Motor optimization objectives (efficiency and torque ripple at nominal condition). The dots show the analysed individuals throughout different generation. Diamonds show Pareto front results.

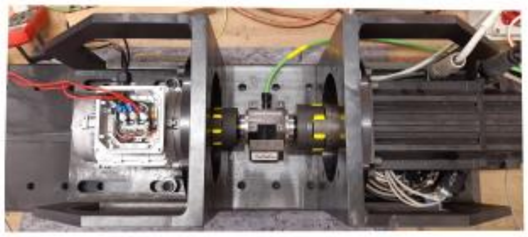

Fig. 7. Test bench used during the experimental measurements. On the left the prototype under test. On the right the master motor to impose the drive speed. In the middle, the torque meter is visible.

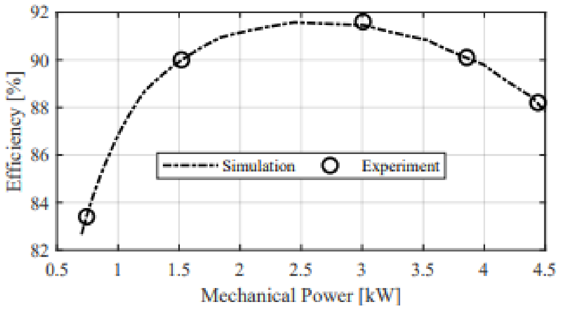

Fig. 8. Motor efficiency at different load, experiment and simulation comparison. Operation at rated speed.

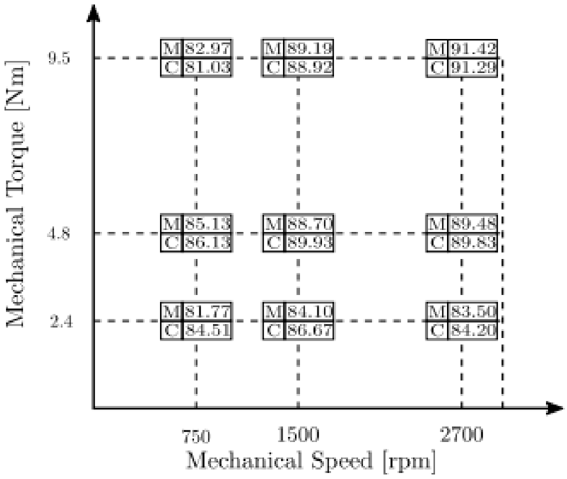

Fig. 9. Motor efficiency at different speed and torque. The test operating conditions required by the standard are included. The measurement results (M) are compared with those obtained from the computation (C) by means of the efficiency model.

C. Design for a specific motor efficiency class

The developed efficiency model is applied to the study how does the efficiency class of the motor change by varying battery length and taking into account different power levels. That is very useful information in the design phase because it allows you to choose the most suitable pile length to make desired output power at a given efficiency level. The efficiency requirements for non-standard power ratings calculated according to the indicated interpolation method in IEC 60034-30-2.Fig 10 shows the results of the analysis. different stacks Motor length is taken into account, up to the maximum length allowed by the size of the frame. Each pile length corresponds to one different engines. For each motor, different mechanical loads are are reviewed and evaluated for the respective effectiveness level. As expected, over the entire length of the stack, the output increases energy creates a lower efficiency class. Also to note that the cost of the motor increases with the length of the pile. From the automaker's point of view, the results reported in Fig 10 give two different interpretations. Firstly, it allows to choose the maximum rated power for the stationary motor length. For example, with a pile length of 100 mm, ie max for considered frame size, motor reaches 3.5 kW in class IE5 or 4.4 kW in class IE4. Is considering other stack length, for example 72mm, motor is IE5 type up to 2.3 kW, type IE4 up to 3.0 kW and type IE3 up to 3.4kW. On the other hand, Fig 10 allows to consider how minimize stack length, i.e. engine cost, for a fixed time nominal power and desired efficiency level. For example, if 3.0 kW motor required, minimum stack length for one The IE3 class motor has a size of 64 mm (point A). Similarly, the required stacking length is 72 mm for motor class IE4 (point B) or 86 mm for IE5 performance class (score C).

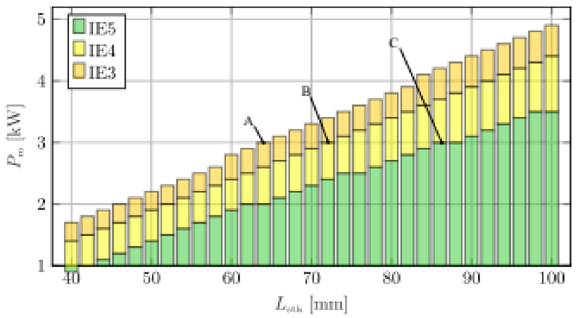

Fig. 10. Motor efficiency class according to different stack lengths and mechanical powers.

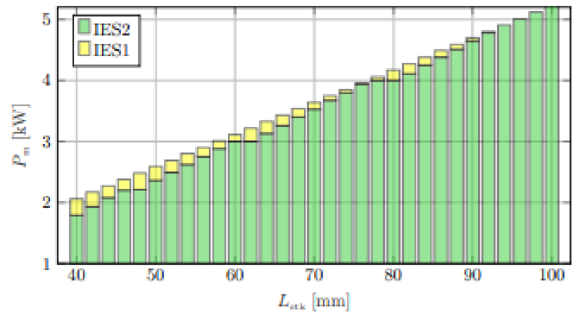

Fig. 11. PDS efficiency class according to different stack lengths and mechanical powers.

D. Design for a specific PDS efficiency class

The same approach of subsection IV-C can be applied to performance class rating of the PDS in which the engine has operate. In this case, as described in subsection III-B, the motor is supposed to be powered by IE2 class CDM so to meet the requirements of EU Regulation 1781/2019. So it is possible to study the effect of the results PDS for different motor stack length. Results are reported in Fig 11. According to IEC 61800-9-2, when The output power of the PDS is between two standard values, Relative loss of RPDS with next higher nominal power taken into account when determining the type of IES. Fig 11 is also possible read in two directions. For the selected stack length, it determined for each respective power PDS efficiency class. In addition, it is possible to determine stack length needed to get the desired PDS efficiency class at a certain nominal power. In Fig 10 and 11, the maximum power is considered for each pile length fixed according to the thermal limit of the engine.

5.CONCLUSION

This article deals with the design of high-performance motors and PDS according to efficiency standards. A design approach where the specification of the motor to achieve a specified level of efficiency is presented. effective The requirements can be specified for the motor, for the PDS or for the whole system. For this, the consideration of all stakeholders standards and detailed explanations of the calculations for efficiency classes are presented for the first time.The analysis considers nominal power from 0.18 kW to 15 kW. With these assumptions, Fig 4 shows motor skills in the classroom IE5 and IE4 must achieve PDS for IES2 performance class for low power PDS (ie up to 0.25 kW). In case higher power, IE3 type motor can also suffice for meets the performance requirements of IES2 PDS, though in the field In this case, the engine must work very well (or In addition, MDP will show less loss than at RCDM).As a concrete example, the design of the 3 kW PDS is is considered. The engine geometry has been optimized for rated power, then it is shown how to modify the design to meet specific efficiency constraints both in terms of motor or PDS for different capacity. Engine the geometry remains the same and only the stack length of engine is changed. It is very important from an industrial point of view perspective in which the same engine stratification is applied to Different products cover different applications and powers ratings. Therefore, the presented approach is very useful in the design of new products when there is a best compromise between The performance and cost of the motor must be determined.The model applied to calculate the efficiency is fully confirmed through review test results different loads. The standard requirements for instrumentation in such tests are also stated.

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