Design of electric motors and power drive systems according to efficiency standards

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***Abstract*—The focus of this paper is the design of high efficiency electric motors adopted in power drive systems. The last efficiency standards are considered as constraint for the motor and drive design: they are introduced and described and their impact on the choice made during the design process are highlighted. As a particular case, the perspective of a motor manufacturer is adopted in order to understand which is the proper efficiency level of the motor required to fulfil the efficiency requirements of the power drive system. This is not always clear and easy to understand because different standards apply in the two contexts. A design example of an industrial motor with 3 kW power is included, showing also experimental results on a prototypes. Also the standards related to the experimental tests, in particular those prescribing instrument accuracy, are considered and commented in the paper.**

***Index Terms*—High efficiency motors, Energy Saving, Efficiency classes, Power Drive System, Complete Drive Module, Electric Motor**

I. Introduction

A great effort has been made in recent years to improve the energy efficiency of human activities and to reduce CO_2 emissions in the next future. Among the others, it is worth to mention the Kyoto Protocol which signature commit the European Union to achieve the so called target 20-20-20 by 2020. To realize such goals, one of the most important measures taken by the EU is the Energy related Products (ErP) Directive 2009/125/EC [1]. The ErP Directive, also called the European Eco-Design Directive, establishes minimum energy efficiency requirements for products that are manufactured or imported into the European Union. It also requires that all products that consume electricity are assessed in relation to energy performance. Such a category includes also electric drives and, as a consequence, many standards and regulations regarding efficiency requirement in products have been published. The European standard EN 50598-2 [2] defines the procedure and the test points that have to be considered in order to determine the energy class and the losses of electronic converters and drives for voltages up to 1000 V and rated power up to 1 MW. The efficiency class is defined by comparing the losses of the real system with those of an ideal reference system. The standard EN 50598-2 has been overcame by the standard IEC 61800-9-2 [3] which deals with ecodesign of power drive systems, power electronics and their driven applications. The standard framework is completed by two other documents: IEC 61800-9-1, that considers applications other than electric drives, and EN 50598-3, which defines the procedures to adopt to determine the Environmental Product Declaration. In the recent years various studies addressing policy and application of these standards have been carried out [4]–[6].

Another important group of regulations, i.e.the 60034-30-1, 60034-2-1 and 60034-30-2 [7]–[9], define the procedures to adopt in order to determine the losses and efficiency class of electric motors. The standard 60034-30-1 defines the efficiency classes for grid sinusoidal supply while the 60034-30-2 considers operation with inverter. The IEC 60034-2-1 standard establishes specific test methods and instrumentation requirements for test of electric machinery. The standard IEC 60034-2-3 [10], recently updated, specifies test methods and interpolation procedure for determining losses and efficiencies of converter-fed motors. Both synchronous and induction machines are covered and the motor is considered as part of a variable frequency power drive system (PDS).

Electric motors are strictly regulated by EU Regulation 1781/2019 [11] which repeal EU 640/2009 [12]. This standard sets the following time table for minimum energy efficiency requirements for electric motors: from 1 July 2021 the energy efficiency of three-phase motors with a rated output from 0.75 kW up to 1000 kW shall correspond to at least the IE3 efficiency level. From 1 July 2023 the energy efficiency of three-phase motors with a rated output equal to or above 75 kW and equal to or below 200 kW, shall correspond to at least the IE4 efficiency level. Specific prescriptions are given for special application motor such as explosion-protected motors, single phase and other low power rating motors. A novelty introduced by the EU 1781/2019 Regulation is the prescription of minimum efficiency requirement also for variable speed drive, i.e. the inverter, of the motors: from 1st July 2021 the power losses of variable speed drives operating motors with a rated power equal to or above 0.12 kW and equal to or below 1000 kW shall be in the IE2 efficiency class.

Besides regulations for electric motor and drives, also standards related to the specific product are of great interest. As an example, companies that supply components, complete fans, or that integrate electric motors and fans into their products, must all meet the requirements established by the ErP Directive. In fact, both the motor and the fan are affected by the legislation. The implementation of the ErP Directive for the ventilation industry are represented by EU Regulation 327/2011 [13] about environmentally friendly design for fans driven by electric motors with input power between 125W

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and 500kW, its extension 1253/2014 and the EU Regulation 1781/2019 [11] on electric motors. The regulations establish minimum levels of efficiency so as the overall efficiency levels of the fan, motor and driving system are reached. Similar standards are under development also for other fields, such as water pumping.

When a complex system is considered, such as a fan or a pump, it is not trivial to understand which is the efficiency required to each single component, i.e. the drive, the motor and the impeller, in order to satisfy the requirements of the final product standard. This is particularly relevant when the system is assembled with products supplied by different manufacturers. A lot of research deals with the topic of losses estimation in electrical machine and power converter, considering also the effect of current and/or voltage distortion of the power electronic on the electrical machine [14]–[22]. In the prospective of moving up efficiency of electric motors, in particular for those industrial applications where squirrel cage induction motors (IM) are extensively employed, many different solutions have been proposed. For instance, optimization of stator and rotor geometry, replacement of aluminium with copper in rotor cage or replacing IM with synchronous motors. Synchronous motors are the favourite candidates for higher efficiency class motor since they not suffer of rotor losses. Among the various possible rotor configuration for synchronous machine, the permanent magnet (PM) assisted synchronous reluctance machine appear to be the most promising since it combines the benefit of PM excitation and reluctance torque exploitation [23]–[25]. Nevertheless, suh a machine configuration presents some critical aspects that have to be carefully considered during the design stage of the drive. Rotor flux barriers have to be properly designed in order to avoid torque ripple. Moreover the motor parameters exhibit strong non linear characteristic which can lead to complexity in the motor control, especially when sensor-less operation is desired. Furthermore, other aspects complicate the replacing of existing motors with premium efficiency motors, such as the environmental impact of industries producing new motors and/or the economic investment required. The manufacturing of new motors could require a consistent amount of energy and materials, leading to a non-negligible environmental impact. Concerning these problems, some solutions have been proposed, such as no-tooling-cost or high-efficiency-remanufacturing strategies [26], [27].

This paper presents a detailed efficiency evaluation for a low power electric drives with a power rating from 0.18 kW to 15 kW, which are typical sizes for industrial applications. The various mandatory standards in this application are considered and a comparative analysis on the different specifications on the efficiency levels is presented. In particular, the perspective of a motor manufacturer is adopted in order to understand which is the proper efficiency level of the motor in order to fulfil the efficiency requirements of the power drive system [28]. As a specific case study, the design of a 3 kW high efficiency motor is presented. The design is optimized for the nominal power rating and then it is investigated how the efficiency class of both the motor and the PDS (in which the motor is adopted) changes scaling the design to fit other power ratings with the same geometry. The adopted design procedure presented in the paper has been verified and validated with experimental test on a real motor. Also the measurements on the prototype, as well as the motor design, has been carried out following the standards on energy efficiency.

II. Review of Standards and Regulation for Efficiency Class Definition and Computation

There are multiple standards and regulations involved in the definition of the efficiency class, its determination and measurement. This Section gives an overview of the actual situation considering especially European IEC standards. The main standards are: the IEC 61800-9-2 [3] dealing with the ecodesign of power drive systems, power electronics and their driven applications; the group of 60034 standards [7]–[10] which define efficiency classes of electric motors and the related test procedures. In particular, the standard IEC 60034-2-3 [10] defines test methods for determining losses and efficiency, including also instrumentation requirements, for converter-fed AC motors, covering both induction and synchronous machines. Besides IEC standards, IEEE published a guide for testing permanent magnet synchronous machines [29]. The focus is not only on efficiency, also general view about test procedures for synchronous machines is given.

In addition to these standards, some other more specific regulations specifically dedicated to the particular application could apply. For example, specific standard for ventilation systems and pumps are currently under development. This last case is, however, beyond the scope of this paper and is not included in the following discussion.

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

Fig. 1 shows the layout of an extended product as considered in the standard IEC 61800-9-2. It includes the electric drive, the load and any other components included in the application such as, for example, mechanical joints, belts or gearbox. The same nomenclature for the system parts is used in this paper. The standard introduces efficiency class definitions for the power drive system (PDS) and the complete drive module (CDM). The PDS is composed by the CDM and the electric motor, including also the feeding section and auxiliaries devices. As an example, cables, switches and fuses are considered within the feeding section. Input and output filters of the CDM are considered within the auxiliaries.

1) Computation of IES class for PDS manufacturers: this section details the efficiency class definition when a whole PDS is available. This is the case of PDS manufacturers that produce both the CDM and the motor. The definition of the efficiency class is based on the computation of the losses of the system. Fig. 2 shows the flow chart of the procedure for PDS efficiency class computation as specified in the standard. According with the standard nomenclature, upper-case letter P refers to absolute losses and lower-case letter p refers to relative losses. Moreover, the operating point is specified when relevant. As an example, $p_{\mathrm{L,RPDS}(90;100)}$ are the relative losses of the reference PDS at 90 % of rated speed and 100 % of rated torque.

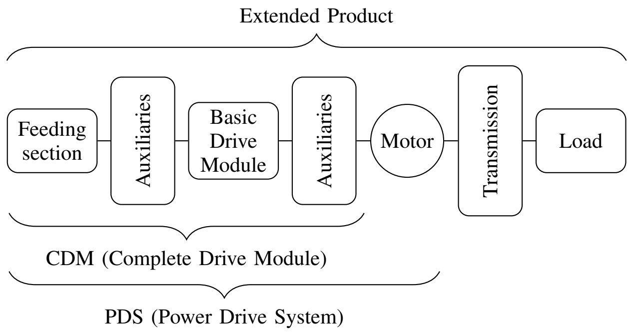

Fig. 1. Extended product overview as defined by IEC 61800-9-2 [3]. The CDM consists of the variable voltage and frequency power converter. The PDS includes the CDM and the electric motor. Finally, the extended product include also the load and the transmission (such as the fan or pump plus the mechanical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

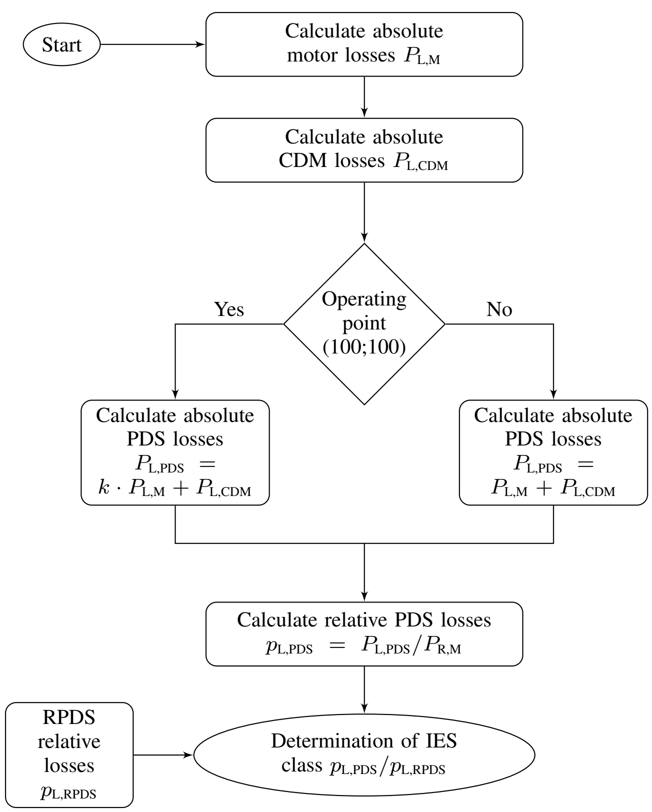

Fig. 2. Procedure to compute the IES class for PDS as specified in standard IEC 61800-9-2 [3].

The process starts with the calculation of the actual losses of the motor $P_{L,M}$ and the actual losses of the CDM $P_{L,CDM}$. The total PDS relative losses $p_{L,PDS}$ are then computed taking into account also the specific working point of interest. Finally, the resulting efficiency class for the PDS is computed comparing the PDS relative losses $p_{L,PDS}$ with those defined in the standard for a reference system of similar power $p_{L,RPDS}$, i.e. considering the ratio $p_{L,PDS}/p_{L,RPDS}$. For the definition of the IES class, the standard defines the operating point at 100 % of rated torque and 100 % of rated speed. Three IES efficiency classes are defined for PDS:

- IES1 class if $p_{\mathrm{L,PDS}}$ are within $\pm 20\,\%$ of $p_{\mathrm{L,RPDS}}$;
- IES0 class if $p_{\mathrm{L,PDS}}$ are at least 20 % higher than $p_{\mathrm{L,RPDS}}$;
- IES2 class if $p_{\mathrm{L,PDS}}$ are at least 20 % lower than $p_{\mathrm{L,RPDS}}$.

When operating a CDM at rated voltage, an over-modulation problem could occur and, in the worst case, the impossibility to operate the motor at rated speed. In order to avoid this problem, the losses of RCDM are given at 90 % of rated motor speed (i.e. $p_{\mathrm{L,RCDM(90;100)}}$ is adopted). It can be assumed that the losses of a CDM at 90 % of the rated speed are the same as at nominal operation. As far as the electric motor is concerned, being supplied by a CDM which cannot provide the rated fundamental voltage at rated speed, it is subjected to higher losses due to the increased motor current. Therefore, in order to consider this problem, the losses of the motor given at rated speed and torque, i.e. $p_{\mathrm{L,RM(100;100)}}$, are increased with the coefficient k, as reported in Fig. 2. As specified in the standard, supposing a voltage drop on the CDM of 10 %, the losses are expected to be increased by 11 %. In this case it follows that $k = 1.11$.

2) Computation of IES class for motor manufacturers: an important situation foreseen by the standard is the possibility to calculate the IES class for a PDS when only a part of the components is available. This is the case, for example, of a motor manufacturer that want to predict the IES class of a PDS realized with its electric motors. In this case, they could define the IES class supposing the motor operated by a CDM, referring to losses specification reported in its data-sheets. Another situation is when there are not a defined CDM for the final PDS, therefore the motor should be supposed to be operated by a RCDM with the losses specified in the standard IEC 61800-9-2.

As reported in the flow chart of Fig. 2, if the motor losses are given at rated speed, as commonly is in data-sheets, the coefficient k shall be used for motor losses correction. The resulting relative PDS losses are computed as:

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

where $P_{\mathrm{L,CDM(90;100)}}$ are the CDM losses, $P_{\mathrm{r,M}}$ is the motor mechanical power and $P_{\mathrm{L,M(100;100)}}$ 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 $p_{\mathrm{L,PDS}}/p_{\mathrm{L,RPDS}}$.

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

The standard IEC 60034-30-2 defines IE efficiency classes of motors for variable speed applications, therefore in this case motors are considered fed by a frequency converter.

This standard defines five classes (from IE-1 to IE-5) of efficiency depending on the motor rated power and rated speed.

The efficiency of a motor for IE class definition shall be measured at 100 % of rated torque and 90 % of rated speed, thus efficiency at n_{90} is labeled η_{90}. Since converters are subject to voltage drop, the requirement to test motors at n_{90} ensure

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)

that the motor is operated at its maximum magnetic flux avoiding over-modulation.

In order to consider the reduced efficiency of the motor operated at partial speed, a correction coefficient r_{HL} for the losses is introduced. This is 0.15 for motors up to 90 kW. Besides including the efficiency drop at partial speed, the coefficient r_{HL} considers also the additional losses due to inverter modulation.

C. Regulation on test methods

The introduction of the premium efficiency classes in the international standards, has an important impact also on the accuracy requirements on instruments adopted in the measurements. Higher the efficiency class, in fact, lower the losses to measure and hence a more accurate measurement setup is required. Moreover, higher efficiency classes are characterized by lower losses differences. Among the different efficiency measurement methods described, the preferred is the input-output method where the efficiency is computed by ratio of output and input power.

For either the electric motor and the PDS measurements, the output power P_{out} is the mechanical power computed from the mechanical torque T_m and the mechanical speed n_m, both measured at the motor shaft.

The input power of a PDS correspond to the electrical power on the grid side of its CDM. Such a power is typically at grid frequency. When the efficiency of an electric motor is evaluated, the input power is evaluated at the output of the CDM. These two power measurements are quite different since the output of the CDM is typically a variable frequency PWM waveform. The measurement complexity of the high frequency harmonic spectrum caused by the inverter is significant and has to be properly managed by the instrumentation.

In Tab. I the instrument requirements defined in the standards are reported, comparing the requirements for measurement on a PDS (standard IEC 61800-9-2) with those for electric motors (IEC 60034-2-3). It is clearly noticeable the more restrictive requirements introduced in the standard IEC 60034-2-3. In particular, the power meter has to ensure an accurate measurement of the additional losses caused by the invert modulation. For this reason the power meter should have an accuracy of 0.3 % or better at least up to 10 times the switching frequency f_{sw}. Moreover, at a 50/60 Hz the accuracy requirement is 0.2 %. It should be noticed that in the IEC 60034-2-3 the power meter accuracy is given at 50/60 Hz even though the rated frequency of an electric motor supplied by a drive could be different. Regarding the torque measurement for electric motor, the IEC 60034-2-3 introduce an increased accuracy requirement for high efficiency motors. In accordance with a more wide mechanical speed range allowed for motors operated by inverted, the standards IEC 60034-2-3 specifies a less restrictive accuracy requirement 0.03 % for a speed measurement above 3000 rpm.

In case of test on the electric motors, the IEC 60034-2-3 reports the set-up requirements for the converter in order to establish the conditions for a repeatable test condition. The main constrain regards the inverter switching frequency, which has to be lower than 5 kHz for motors with a rated speed up to 3600 rpm, or lower than 10 kHz for a rated speed above 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

III. 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

To define the IES class, the real PDS losses have to be compared with those of the RPDS. Tab. II shows the standard specifications for the considered a motor drive system. In particular, the relative losses, p_L are reported for all the RCDM, RM and RPDS. In the table also the absolute losses value are reported, computed as $P_L = p_L \cdot P_{r,M}$ for the RM and the RPDS, and as $P_L = p_L \cdot S_{r,equ}$ for the RCDM, where $S_{r,equ}$ is the output apparent power of the CDM.

Then, the efficiencies for RM and RPDS are computed as:

$$\eta = \frac{P_{r,M}}{P_{r,M} + P_L} \tag{2}$$

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}[%]	$P_{\mathrm{L,ref}}$ [W]	$k \cdot P_{\mathrm{L,ref}}$ [W]	$P_{\mathrm{L,PDS}}$ [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 ($P_{\mathrm{r,CDM}}$) that is not provided by the standard. Anyway, knowing RM mechanical power and its losses, the active power of RCDM can be assumed as:

$$P_{\mathrm{r,CDM}} = P_{\mathrm{r,M}} + P_{\mathrm{L,RM}} \tag{3}$$

and then RCDM efficiency computed as:

$$\eta = \frac{P_{\mathrm{r,CDM}}}{P_{\mathrm{r,CDM}} + P_{\mathrm{L,RCDM}}} \tag{4}$$

B. IES class computation using a RCDM

This Section illustrates the computation of the IES efficiency class for the PDS when only the motor is considered. Some general considerations about the procedure here presented were given in section II-A2. According to the EU regulation 1781/2019, the CDM must meet IE2 efficiency class. Since the CDM is not available, the power losses provided in the regulation have been adopted, i.e. 25 % lower than the RCDM. Therefore, starting from the RCDM specified in Tab. II, the losses of the adopted CDM are $P_{\mathrm{CDM}} = 0.75 \cdot P_{\mathrm{RCDM}} = 223.78\,\mathrm{W}$. Being the CDM losses fixed by the standard, the final IES efficiency class of the PDS will depend on the actual efficiency of the motor. For the sake of generality and in order to obtain some general information useful for the design of the motor, different efficiency classes are considered. In particular all the five classes from IE-1 to IE-5 as reported by IEC 60034-30-2 are considered and the actual losses are computed as follow:

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

The actual losses are necessary to compute the IES PDS efficiency class and the values are reported in Tab. III. For the sake of completeness, also the losses with the correction factor k are reported, as required in the flow chart of Fig. 2. The last column in the table shows the resulting PDS losses, computed as sum of each motor losses and the RCDM losses, i.e. $P_{\mathrm{L,PDS}} = k \cdot P_{\mathrm{L,ref}} + P_{\mathrm{L,RCDM}}$.

Fig. 3 shows the same results of Tab. III, highlighting the contribution to the total losses of the different system parts. Clearly lower the motor efficiency class, higher the total losses of the PDS. The horizontal lines show the losses levels used in the standard to define the efficiency classes.

Comparing the columns and the level lines, it is easy to evaluate the efficiency class of the PDS. For example if an IE1 motor is adopted, the PDS is clearly in the IES1 efficiency class. Similar considerations are valid also when IE3, IE4 or IE5 motor are adopted, being in this case the PDS clearly in IES2 efficiency class. With an IE2 motor, the situation has to be evaluated more accurately, since the PDS could be either IES1 or IES2 efficiency class depending on the specific losses of the motor. Nevertheless, with the timetable scheduled by the EU Regulation 1781/2019 the PDS must meet the IES2 efficiency level.

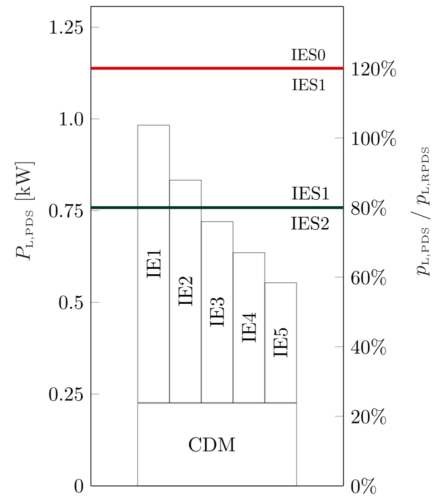

Fig. 3. Losses of a 3 kW mechanical power PDS. CDM losses are estimated using the reference given by the standard. Motor losses are the corresponding losses for motor in IE-1...5 class. PDS class thresholds are reported.

C. Extension of the motor power range

The approach presented in the previous section has been extended to consider a power range, from 0.18 kW to 15 kW. The normalized power ratings in IEC 60034-30-2 and in IEC 61800-9-2 are included in the analysis. Such a power range covers many practical installations, from household appliances to industrial applications. Fig. 4 shows the losses computation for all the power ratings highlighting also the PDS efficiency classes. In order to improve the readability, the results are presented in terms of the ratio $p_{\mathrm{L,PDS}}$ / $p_{\mathrm{L,RPDS}}$. This allows also to observe the behavior of the efficiency requirements changing the rated power of the PDS. The data about the 3.0 kW PDS, are the same as reported in Fig. 3.

It is interesting to observe how the restriction changes moving toward higher power ratings. Along all the power range an IES2 class PDS is obtained adopting an IE3, IE4 or IE5 motor. As the power rating increases, a IES2 class PDS could be realized adopting either an IE2 motor.

IV. MOTOR DESIGN OPTIMIZATION FOR A SPECIFIC EFFICIENCY CLASS

This Section considers the design of a motor to meet specific efficiency class requirements. The motor is expected to operate in a variable speed drive for centrifugal machines, such as ventilation and pumping systems. In such applications, the nominal data are not always constrained standard values and different applications could require a slightly different power

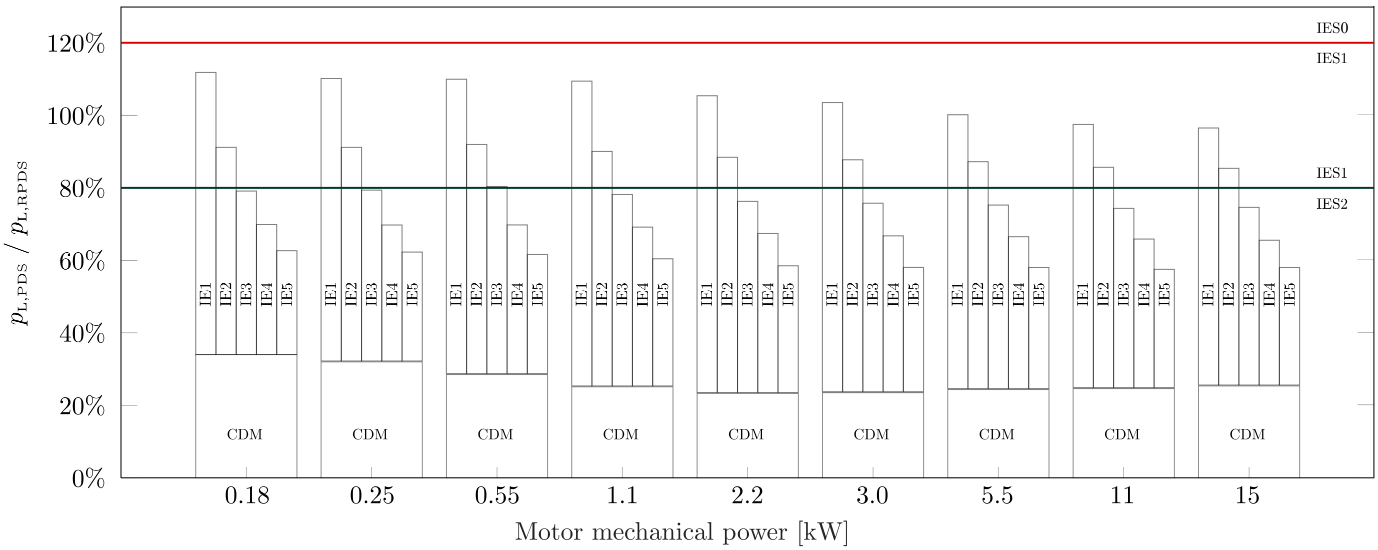

Fig. 4. Percent PDS losses relative to reference PDS losses, for different mechanical rating powers. CDM losses are estimated using the reference given by the standard. Motor losses are the corresponding losses for motor in IE-1...5 class. PDS class thresholds are reported.

rating. Therefore, the design of the motor has to be rearranged in order to meet the specified power and speed with the given efficiency class. Of course a motor configuration, i.e. lamination geometry and winding configuration, has to be adopted for more power ratings which are close enough. This is clearly to limit the costs of production.

The procedure is illustrated considering a motor with a power rating of about 3 kW. The same motor geometry will be adopted for all the motors in the power range around such a value adjusting the stack length and the number of turns.

A. Design of the motor configuration

The starting point for the motor design is an existing IM with nominal power of 3 kW with a fram size IEC 80 [30]. Additional constraints are fixed by the motor manufacturer: the same frame size and stator lamination has to be adopted for the new design. Also the number of poles and winding configuration cannot be changed in order to limit the production costs. Torque profile has to be smooth in order to limit vibration and noise of the system.

Additional requirements are specified also for the drive, in particular the motor should run both with sensored and sensorless controls. Moreover the motor can be provided as part of a PDS sold directly by the manufacturer, or as a motor to be coupled by customers with third party inverters. Considering the given constraints, an interior permanent magnet (IPM) configuration has been selected for the rotor of the new design. Therefore, only the rotor geometry has been designed adopting optimization techniques: finite element 2D simulations are used to carefully evaluate the design and to achieve the best candidate [22], [32]. In order to identify the best configuration to satisfy the aforementioned constraints, the considered optimization objectives are the maximum efficiency at nominal operation and minimum torque ripple. Fig. 5 shows a sketch of the rotor geometry along as the optimization variables considered during the design optimization. They are the air gap thickness g which is considered nonuniform via the thickness Δg in order to reduce the torque ripple and to improve the harmonic spectra of the back-emf; the magnet thickness t_m and the pole angle ϑ_p.

The optimization is based on a differential evolution algorithm coupled with finite element simulations. Besides the rotor quantities reported in Fig. 5, other optimization variables were the stator current density, the PM thickness and the stack length. As constraints, the minimum airgap was fixed at 0.3 mm, the maximum stack length at 100 mm and the maximum current density at 7 A/mm^2 RMS. For the PM thickness, a minimum value of 3 mm has been fixed on the basis of demagnetization requirements.

Fig. 6 shows the objectives plane obtained from the optimization. Efficiency is computed at nominal power rating operation. The individual motors are compared for the same nominal electromagnetic torque. It is worth to notice the significant reduction of the torque ripple, which is reported in percent of the nominal torque. The individual chosen in the objectives space, is located at 93.1 % of efficiency and 4.8 % of torque ripple. Once the rotor lamination has been selected, it is possible to define the motor configuration, i.e. the specific stack length L_{stk} to meet precise efficiency requirements on the motor or the PDS, as described in subsection IV-C and subsection IV-D respectively. To this aim, an accurate efficiency model for the actual machine design is mandatory. Such a model is detailed in the next Section.

B. Efficiency determination model

Since the same motor configuration is adopted to adjust the rated power of the PDS, it is important to have an accurate model to compute the motor efficiency for different stack length. This is achieved combining the results of finite element simulations with an analytical model of the motor to scale the results at the actual machine lengths. In order to increase the accuracy of the model, specific tests have been made to

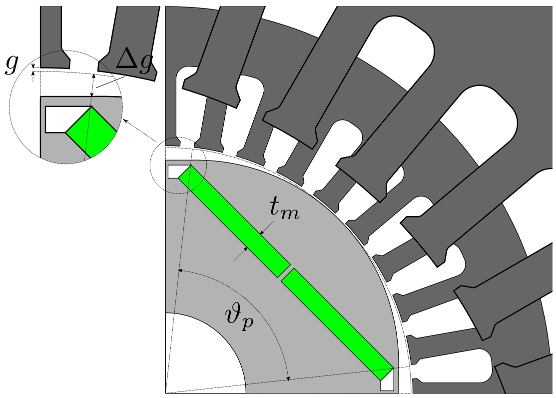

Fig. 5. Geometry of the IPM motor designed with the variables considered during the optimization.

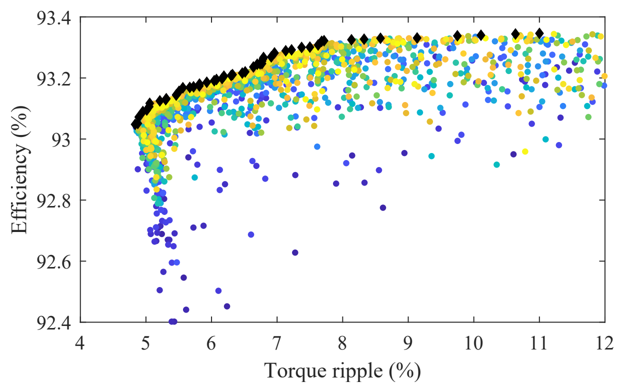

Fig. 6. Motor optimization objectives (efficiency and torque ripple at nominal condition). The dots show the analysed individuals throughout different generation. Diamonds show Pareto front results.

carefully evaluate the mechanical losses of the motor. Such test carefully characterize the bearing and windage losses and specific data have been provided by the motor manufacturer.

For a given speed, a unit stack length (L_{stk}) of the motor is simulated by means of FE simulations considering different feeding currents, in order to find the electromagnetic power $P^{FEA}_{\text{EM,pu}}$. A proper current range has been considered according to thermal limits of the motor.

In the following, the subscript pu refers to quantities given for unit stack length and the superscript FEA indicates quantities computed by means of finite element analysis. Other quantities are derived analytically as described in the following. Once $P^{FEA}_{\text{EM,pu}}$ is computed, the rated mechanical power P_M for a specific L_{stk} is computed as:

$$P_{\text{M}} = P^{\text{FEA}}_{\text{EM,pu}} \cdot L_{\text{stk}} - P^{FEA}_{\text{Lfe,pu}} \cdot L_{\text{stk}} \cdot K_{\text{HL}} - P_{\text{Lwi,pu}} \cdot L_{\text{stk}} - P_{\text{Lbr}} - P_{\text{Lfan}} \quad (6)$$

where iron losses $P^{FEA}_{\text{Lfe,pu}}$ and mechanical losses are considered. The latter component is divided into airgap windage losses $P_{\text{Lwi,pu}}$, bearing losses P_{Lbr} and self-ventilation fan losses P_{Lfan}. 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 P_E to the motor is computed as:

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

where $P_{\text{LJ,pu}}$ represent the Joule losses of the in-slot winding in pu, and P_{LJew} 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 K_{HL} in both iron losses and Joule losses. According to the standard IEC 61800-9-2, its value is set to 1.15.

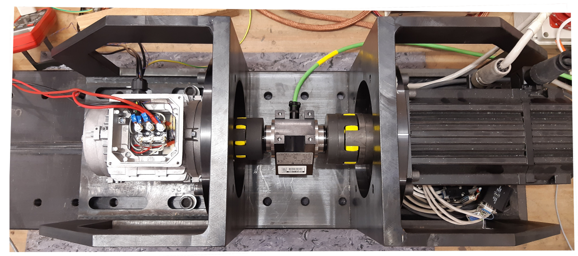

Fig. 7. Test bench used during the experimental measurements. On the left the prototype under test. On the right the master motor to impose the drive speed. In the middle, the torque meter is visible.

A prototype of the new motor has been built and tested to validate the design. Fig. 7 shows a picture of the test bench adopted for the test. Fig. 8 shows a comparison between experimental results and computations of the motor efficiency for different loads, including operation at overload. The winding temperature variation with different loads has been included in the analysis. Operation at rated speed is considered. Efficiency measurements have been carried out according to the standard as reported also in sec. II-C. In particular instrumentation suitable to measure efficiency of IE5 motor has been adopted.

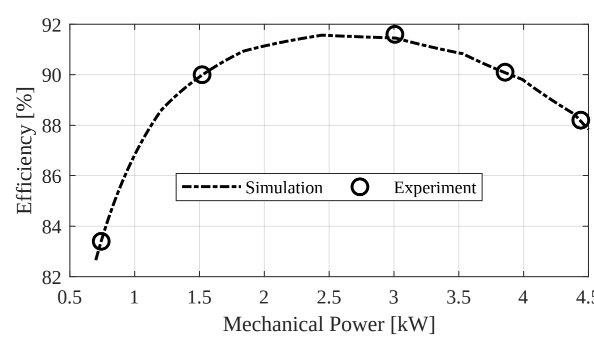

Fig. 8. Motor efficiency at different load, experiment and simulation comparison. Operation at rated speed.

The motor has been tested also at partial loads as suggested by the standard. Operations at different torque and speed values have been reproduced on a test bench. Fig. 9 shows the comparison between experimental measurement (M) and computation with the described efficiency model (C). A very good agreement can be noticed for medium and rated load. There is a larger discrepancy in the predicted efficiency value

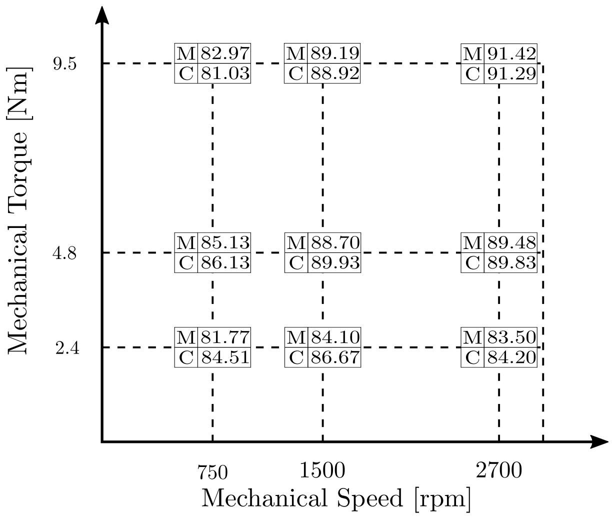

Fig. 9. Motor efficiency at different speed and torque. The test operating conditions required by the standard are included. The measurement results (M) are compared with those obtained from the computation (C) by means of the efficiency model.

at very low load. Nevertheless, this does not impact the capability of the model to predict the correct efficiency class for the PDS.

C. Design for a specific motor efficiency class

The developed efficiency model is adopted to investigate how the efficiency class of the motor changes varying the stack length and considering different power ratings. This is a very useful information during the design stage since it allows to select the most adequate stack length to realize the desired output power in a given efficiency class. The efficiency requirements for non-standard power ratings have been computed according to the interpolation method reported in the standard IEC 60034-30-2.

Fig. 10 shows the results of the analysis. Different stack lengths of the motor are considered, up to the maximum length allowed by the frame size. At each stack length correspond a different motor. For each motor, various mechanical loads are considered and the corresponding efficiency class is evaluated. As expected, for all stack length an increase of the output power yields a lower efficiency class. It is also worth to notice that the motor cost increases with the stack length.

From the motor manufacturer point of view, the results reported in Fig. 10 offer two different interpretations. At first, it allows to select the maximum rated power for a fixed motor length. As an example, with a stack length of 100 mm, i.e. the maximum for the considered frame size, the motor achieves 3.5 kW within IE5 class or 4.4 kW in IE4 class. Considering another stack length, for example 72 mm, the motor is in IE5 class up to 2.3 kW, in IE4 class up to 3.0 kW and in IE3 class up to 3.4 kW.

On the other hand, Fig. 10 allows to consider how to minimize the stack length, i.e. the cost of the motor, for a fixed power rating and a desired efficiency class. As an example, if a 3.0 kW motor is required, the minimum stack length for an IE3 class motor is 64 mm (point A). Similarly, the required

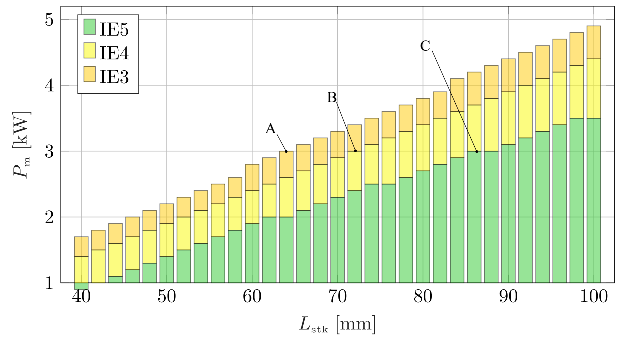

Fig. 10. Motor efficiency class according to different stack lengths and mechanical powers.

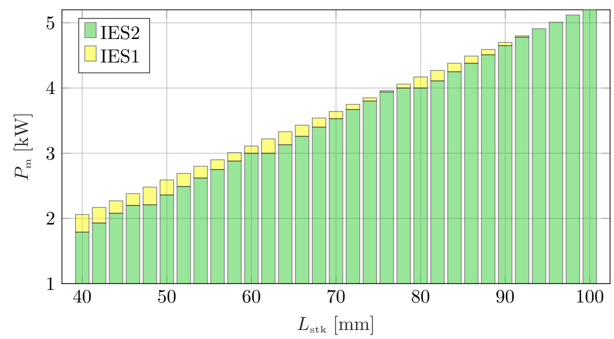

Fig. 11. PDS efficiency class according to different stack lengths and mechanical powers.

stack lengths are 72 mm for an IE4 class motor (point B) or 86 mm for IE5 efficiency class (point C).

D. Design for a specific PDS efficiency class

The same approach of subsection IV-C can be adopted to evaluate the efficiency class of a PDS in which the motor has to operate. In this case, as described in subsection III-B, the motor is supposed to be supplied by a IE2 class CDM in order to satisfy the requirement of the EU regulation 1781/2019. It is hence possible to investigate the efficiency of the resulting PDS for different motor stack lengths. The results are reported in Fig. 11. According to the standard IEC 61800-9-2, when the PDS output power is between two standard values, the relative losses of the RPDS with the next higher power rating are considered for IES class determination. Also Fig. 11 can be read in two directions. For a selected a stack length, it allows to identify for each power rating the corresponding PDS efficiency class. Alternatively it is possible to determine the required stack length to have a desired PDS efficiency class at a given rating power.

In both Fig. 10 and Fig. 11, the maximum power considered for each stack length is fixed according to the thermal limit of the motor.

V. Conclusion

This paper deals with the design of high performance motor and PDS according to efficiency standards. A design approach that allows to identify the motor characteristics to fulfil prescribed efficiency levels has been presented. The efficiency requirements could be specified for the motor, for the PDS or for the whole system. For this, a review of all the involved standards and a detailed explanation of the computations for efficiency classes has been presented at first.

The analysis considers power rating from 0.18 kW to 15 kW. With these assumptions, Fig. 4 shows that motor in classes IE5 and IE4 are expected to realize a PDS in IES2 efficiency class for low power PDS (i.e. up to 0.25 kW). In case of higher power, also motors in IE3 class can be adequate to meet the IES2 PDS efficiency requirements, even if, in this case, the motor has to exhibit very good performance (or alternatively the CDM has to exhibit lower losses with respect to the RCDM).

As a specific example, the design of a 3 kW PDS has been considered. The motor geometry has been optimized for the nominal power and then it is shown how to modify the design in order to meet specific efficiency constraints on both the motor or the PDS for different power ratings. The motor geometry is kept the same and only the stack length of the motor is changed. This is very important from an industrial point of view where the same motor lamination is adopted for various productions including different applications and power ratings. Therefore, the presented approach is very useful in the design of new products when the best trade-off between efficiency and cost of the motor has to be identified.

The adopted model for the efficiency computation has been fully validated by means of experimental results considering different loads. Also the standard requirements for instrumentation during such tests have been highlighted.

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