Feasibility of Ecodesign Standard IEC 61800-9 A Real Case Study

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Abstract—**Ecodesign standard IEC 61800-9 methodology was applied to determine energy efficiency of a real Power Drive System and compare calculated to measured values. The comparative study showed that the method overestimates the losses. The main contribution of this dissertation is the feasibility analysis of the methodology pointing the divergences and presenting possible justifications and improvements.**

Keywords—**Ecodesign, IEC 61800-9, Power Drive System, Energy Efficiency, Motors System.**

I. INTRODUCTION

The compromise to reduce CO_2 emissions directly imply in using more efficient electric equipment and systems. The importance of electric motor systems as a major electricity consumer has been recognized by the European Commission as one of the products to which the Directive 2009/125/EC [1] with Ecodesign requirements should be implemented. 'Ecodesign' means the integration of environmental aspects into product design with the aim of improving the environmental performance of the product throughout its whole life cycle [1].

The new Regulation (EU) 1781/2019 [2] will enter into force next year (2021) making it mandatory for the Power Drive System (PDS) manufacturers to apply the Extended Product Approach (EPA) described by IEC 61800-9 [3] [4] to define the energy efficiency of their products and allowing the load machine manufacturer compute the Energy Efficiency Index (EEI) of the Extended Product (EP).

Standard IEC 61800-9 [3] [4] is a complete analysis of the Extended Product composed of an electric motor, its Complete Drive Module (CDM) and its driven machine (load machine and transmission). This standard proposes a Semi-Analytical Model (SAM) to compute the efficiency of the Power Drive System (electric motor and CDM) in part load conditions and presents the references losses for motors, CDMs and PDSs. The reference losses allow the manufacturers define the efficiency classification for their CDMs and PDSs, similar to what is already done for electric motors.

A. Goals of This Dissertation

The objective of this dissertation is to make a critical analysis of the Ecodesign standard IEC 61800-9 Parts 1 and 2 [3] [4] by the point of view of the Power Drive System manufacturer. The author proposes the following specific goals to approach the main objective:

- Application of the Semi-Analytical Model described by IEC 61800-9-2 [4] to compute the losses and efficiency of a real Power Drive System (PDS) at the operating points recommended by IEC 61800-9-1 [3].
- Comparison between motor, CDM and PDS calculated losses to their respective reference values given by IEC 61800-9-2 [4] with the objective to find the CDM and PDS efficiency classification.
- To validate the methodology, the calculated efficiencies shall be compared to the efficiency values resulting from measurements performed on the real PDS, discussing the divergences, and making a feasibility analysis of the proposed methodology.
- To complete the real case study, the PDS shall be combined with a real driven equipment to compute the Energy Efficiency Index of the Extended Product on the real operation point. An axial fan coupled to a gearbox was chosen and the study focused on computing the minimum axial fan efficiency to comply with Commission Regulation (EU) 327/2011 [5] using the real PDS efficiency at fan operating point.

II. ECODESIGN FOR POWER DRIVE SYSTEM – THE EXTENDED PRODUCT APPROACH

Several standards exist to describe calculation and test methodologies to determine the rated efficiency of singular devices and machines, regardless the system where they are installed or the point of operation. The rated point of operation is defined as the point of highest efficiency.

However, devices and machines do not operate in its optimal point all the time and, in many applications, they never reach their rated point. The reasons are several, for example there is a tendency to oversize electric motors based on a misguided belief that larger motors will operate more reliably for a given application. But the most trivial reason is that system components generally do not have the same rated point of operation all of them, implying that one or more components shall be oversized (as downsizing is not a feasible option).

Equipment operating out of rated point have lower efficiency themselves and reduce the efficiency of the upstream system, and the system efficiency reduction may also impact on its own efficiency, as a chain reaction.

In order to overcome the issue, it is required to understand the losses causes and interdependences in each component of the system and define efficiency references values not only for the rated point, but for other common points of operation.

Extended Product Approach of IEC 60081-9 [3] [4] was written in this realm. This standard is an interdependence analysis of the Power Drive System (PDS) and its driven machine (named Extended Product) based on the specific standards of each equipment and several tests performed on the complete PDS.

The parts of an Extended Product according to IEC 61800-9-1 [3] are following described:

- Complete Drive Module (CDM) – basic drive module (BDM) consisting of the electronic power converter, specifically the variable speed drive (VSD), connected between the electric supply and the motor, as well as its extensions as protection devices, internal transformers, internal cooling system, filters and auxiliaries. Herein referred as the drive device, VSD or CDM.
- Electric Motor – electromechanical equipment that transforms electric power into mechanical power (torque in its shaft end).
- Power Drive System (PDS) – system consisting of a CDM and a motor.
- Motor System – the same as PDS when the system consists of a CDM and a motor; or a motor and its starter devices as softstarter and/or contactors, if CDM is inexistent.
- Driven Equipment – equipment mechanically connected to the motor shaft consisting of the transmission system (gearbox, coupling, pulley-belt, etc.) and the load machine (pump, fan, compressor, conveyor, etc.). Herein referred as load machine, load, or driven machine.
- Extended Product – driven equipment together with its connected motor system or PDS.

This dissertation considers the Motor System as a PDS (VSD and motor) and the driven equipment as an axial fan coupled through a gearbox.

The Extended Product Approach described by IEC 61800-9 [3] [4] employs a Semi-Analytical Model – physical concepts and mathematics algorithms – to calculate the typical relative power loss of each subpart of the Extended Product. It considers the operation point of the most downstream equipment, the load machine, and convert it to upstream ones, in order to determine the overall system efficiency afterwards.

Partial load in the sense of IEC 60081-9 [3] [4] is any operation point which the load requires from the motor reduced torque, power and/or speed compared to their rated values. Peak efficiency usually occurs between 75% to 100% load and has a severe decrease below 50% load.

III. IEC EFFICIENCY METHODOLOGY REVIEW

A. Electric Motor

The Energy Conservation Principle for electric motor can be written as:

$$\begin{pmatrix} Electrical \\ Energy \end{pmatrix} = \begin{pmatrix} Mechanical \\ Energy \end{pmatrix} + \begin{pmatrix} Stored \\ Energy\ in\ the \\ Magnetic\ Field \end{pmatrix} + \begin{pmatrix} Heat \\ Losses \end{pmatrix} \tag{1}$$

The irreversible conversion of energy into losses are due to the following causes:

- Joule losses: part of electrical energy is converted into heat through the electric resistances found by the electric current in stator and rotor.
- Friction and windage losses: part of mechanical energy is converted into heat due to mechanical friction of the rotating parts (as bearings and cooling fan).
- Core losses: part of the stored energy in the magnetic field is converted into heat due to the hysteresis phenomena and the circulation of induced Foucault (eddy) currents in the stator sheets, both caused by the magnetic flux variation in the core.
- Additional load losses: consist of the additional losses that appear due to the leakage magnetic flux, the non-uniform distribution of current in copper wires, and the magnetic flux distortion caused by the load current.

Mechanical power is the force required to rotate the shaft, named torque, as defined in Equation 2.

$$P_{mec} = \frac{T.n_R}{9550} \tag{2}$$

The efficiency shall be computed as the output mechanical power divided by its input electric active power.

$$\eta_M = \frac{P_{mec}}{P_{in,M}} \tag{3}$$

IEC 60034-2-1 [6] defines methods to calculate the total losses considering sinusoidal supply (DOL: direct on line) and IEC 60034-2-3 [7] defines a methodology to compute the additional losses caused by the harmonics created by the CDM and consequently the efficiency of converter-fed induction motors. The following related equations are defined.

$$P_{LS} = 1.5.R_w.I_{in,M}^2 \tag{4}$$

$$P_{Lcte} = P_0 - 1.5.R_w.I_0^2 = P_{LFe} + P_{Lfw} \tag{5}$$

$$P_{LR} = \left(P_{in,M} - P_{LS} - P_{LFe}\right).s \tag{6}$$

$$P_{LRes} = P_{in,M} - P_{mec} - P_{LS} - P_{LR} - P_{Lfw} - P_{LFe} \tag{7}$$

$$P_{L,M@DOL} = P_{LS} + P_{LR} + P_{Lfw} + P_{LFe} + P_{LL} \tag{8}$$

$$\eta_{M@DOL} = \frac{P_{mec}}{P_{mec} + P_{L,M@DOL}} \tag{9}$$

$$P_{LH} = r_H.P_{L,M@DOL} \tag{10}$$

$$\eta_{M@CDM} = \frac{P_{mec}}{P_{mec} + P_{L,M@DOL} + P_{LH}} \tag{11}$$

The residual loss shall be smoothed by using the linear regression analysis based on expressing P_{LRes} as a function of the square of load measured torque (for at least six load conditions). The additional load loss P_{LL} can be determined by offsetting the curve to the origin, as P_{LL} depend on load and at no-load condition the torque is null, so shall be the P_{LL}. For this dissertation purposes $P_{LRes} = P_{LL}$ as the input is the declared manufacturer's total losses.

Maximum harmonic factor is defined by IEC 60034-2-3 as:

- r_H = 15% for converter switching frequency 4 kHz and recommended for motors with P_{mec} < 90 kW.
- r_H = 25% for converter switching frequency 2 kHz and recommended for motors with P_{mec} ≥ 90 kW.

IEC 61800-9-2 [4] brings a different approach to determine motor efficiency and losses at any operating point (torque and speed) based on measured segregated losses at rated condition.

The fundamental supply frequency and output torque are used as relative values referred to their rated values. The relative rated output power is therefore given by Equation 14.

$$f = \frac{f_{load}}{f_{rated}} \tag{12}$$

$$T = \frac{T_{load}}{T_{rated}} \tag{13}$$

$$P = T.f \tag{14}$$

The interpolation equations can be used to find losses in the full base frequency $(f = 0 \dots 1)$ and torque $(T = 0 \dots 1)$ ranges. Extrapolation to the overload $(T > 1)$ range is also possible albeit with increasing error. Extrapolation to the field-weakening speed range $(f > 1)$ is not possible.

For asynchronous motors, the relative speed may also be used for the interpolation instead of the relative supply frequency, thereby disregarding the slip.

The following Equations 15 to 22 are described by IEC 61800-9-2 [4] Annex D to determine the relative losses at any operating point (f, T) considering the segregated losses are known at least for the rated condition.

$$\begin{aligned} P_{LSR}(f,T) = P_{LSR}(f_r,T_r).\Bigg[&\left(\frac{I_0}{I_{in,M}}\right)^2 \\ &+ \left(1 - \left(\frac{I_0}{I_{in,M}}\right)^2\right).T^2\Bigg] \end{aligned} \tag{15}$$

$$P_{LFe}(f,T) = P_{LFe}(f_r,T_r).[K_{Fe}.f + (1 - K_{Fe}).f^2] \tag{16}$$

$$P_{Lfw}(f,T) = P_{Lfw}(f_r,T_r).[K_{fw}.f + (1 - K_{fw}).f^2] \tag{17}$$

$$P_{LL}(f,T) = P_{LL}(f_r,T_r).[K_{LL}.f.T^2 + (1 - K_{LL}).f^2.T^2] \tag{18}$$

$$P_{LH}(f,T) = P_{LH}(f_r,T_r) \tag{19}$$

$$\begin{aligned} P_{L,M@CDM}(f,T) = P_{LSR}&(f,T) \\ &+ P_{LFe}(f,T) + P_{Lfw}(f,T) \\ &+ P_{LL}(f,T) + P_{LH}(f,T) \end{aligned} \tag{20}$$

$$P_{L,M@CDM,Relative}(f,T) = \frac{P_{L,M@CDM}(f,T)}{P_{mec}} \tag{21}$$

$$\eta_{M@CDM}(f,T) = \frac{f.T}{f.T + P_{L,M@CDM,Relative}} \tag{22}$$

B. Complete Drive Module (CDM)

It is the goal of IEC 61800-9-2 [4] to describe the CDM losses as a function of motor torque and speed in the same operating points which the motor's losses are determined with the objective to find the PDS losses afterwards. However, CDM losses depend on its output parameters: fundamental output voltage and current and the phase angle between them. Therefore, it is needed to correlate motor output parameters to CDM output parameters.

First and foremost, motor relative speed shall be considered identical to CDM relative output frequency. At operating points with zero relative frequency, a deviation of up to 12 Hz is allowed.

In second step, motor torque shall be correlated to CDM output current and displacement factor. The CDM output current is the same motor absorbed current and the CDM output displacement factor is considered the same motor power factor.

For asynchronous motors, the torque-producing current is the rotor current. The relation between the absorbed motor current and the torque-producing current is usually provided by motors manufacturers as a performance curve with the values of absorbed current and power factor as a function of relative load, the relative load in these curves shall be interpreted as the torque-producing current. The performance data provided by the motor manufacturer in rated speed/frequency shall be considered identical for any CDM relative frequency.

CDM relative output voltage shall be considered the same as CDM relative output frequency (considering scalar operation mode) within the operation zone (not valid for field-weakening zone). To avoid overmodulation, CDM output voltage shall be limited to 90% of CDM input voltage and consequently CDM frequency shall be limited to 90% CDM rated output frequency.

TABLE I
RELATION BETWEEN MOTOR AND CDM OUTPUT PARAMETERS

Motor output parameter		CDM output parameter
Relative Speed	⇔	Relative Frequency ⇔ Relative Voltage
Relative Torque	⇔	Relative Current Displacement factor

The IEC 61800-9-2 [4] describes the equations 23 to 35 to determine the CDM relative losses as a summation of losses in each part of the CDM.

Some parameters are provided by IEC 61800-9-2 [4] as typical values for a Reference CDM (RCDM). Manufacturers are free to consider the real values of CDM parameters.

$$\begin{aligned} P_{L,on,T} = \sqrt{2}.I_{out}.U_{T,th}.&\left(\left(\frac{1}{2\pi}\right) + \frac{1.22.m.\cos\varphi_{out}}{8}\right) \\ &+ \frac{U_{T,on} - U_{T,th}}{I_{r,out}}.2.I_{out}^2.\Bigg(\frac{1}{8} \\ &+ \frac{1.22.m.\cos\varphi_{out}}{3\pi}\Bigg) \end{aligned} \tag{23}$$

$$\begin{aligned}P_{L,on,D} = \sqrt{2}.I_{out}.U_{D,th}.&\left(\left(\frac{1}{2\pi}\right) - \frac{1.22.m.\cos\varphi_{out}}{8}\right)\\ &+ \frac{U_{D,on} - U_{D,th}}{I_{r,out}}.2.I_{out}^2.\left(\frac{1}{8}\right.\\ &\left.- \frac{1.22.m.\cos\varphi_{out}}{3\pi}\right)\end{aligned} \tag{24}$$

$$P_{L,sw,T} = \frac{E_T}{\pi}.U_{DC}.\sqrt{2}.\left(I_{out} + I_{motor\_cable}\right).f_{sw} \tag{25}$$

$$P_{L,sw,D} = \frac{E_D}{\pi}.U_{DC}.\sqrt{2}.\left(I_{out} + I_{motor\_cable}\right).f_{sw} \tag{26}$$

$$P_{L,inverter} = 6.\left(P_{L,on,T} + P_{L,on,D} + P_{L,sw,T} + P_{L,sw,D}\right) \tag{27}$$

$$\begin{aligned}&P_{L,rectifier}\\ &= 6.\left(\frac{\sqrt{2}}{\pi}.m.\cos\varphi\,.I_{out}.U_{D,th,rec}\right.\\ &\left.+ \frac{U_{D,on,rec} - U_{D,th,rec}}{\cos\varphi_{r,out}\,.I_{r,out}}.\frac{1}{2}.\left(\frac{m.\cos\varphi_{out}.I_{out}}{\lambda}\right)^2\right)\end{aligned} \tag{28}$$

$$\begin{aligned}&P_{L,choke}\\ &= k1_{choke}.k2_{choke}.\sqrt{3}.\frac{\left(\frac{m.\cos\varphi_{out}.I_{out}}{\lambda}\right)^2}{\cos\varphi_{r,out}\,.I_{r,out}}.\frac{U_{r,in}}{\sqrt{3}}\end{aligned} \tag{29}$$

$$\begin{aligned}P_{L,DC_{link}} = k1_{DC_{link}}.I_{r,out}.U_{DC}^2&\\ + k2_{DC_{link}}.&\frac{\left(\frac{\sqrt{3}}{1.35}\cdot\frac{m.\cos\varphi_{out}.I_{out}}{1 + 50.k1_{choke}}\right)^2}{I_{r,out}}\end{aligned} \tag{30}$$

$$P_{L,rails} = \frac{U_{rails}}{I_{r,out}}.I_{out}^2 \tag{31}$$

$$P_{L,control} = 50\ W \tag{32}$$

$$\begin{aligned}P_{L,cooling} = k_{L,cooling}.\big(&P_{L,inverter} + P_{L,rectifier} + P_{L,rails}\\ &+ P_{L,DC_{link}} + P_{L,choke} + P_{L,control}\big)\end{aligned} \tag{33}$$

$$\begin{aligned}P_{L,CDM}(f,T) = &P_{L,inverter}(f,T) + P_{L,rectifier}(f,T)\\ &+ P_{L,rails}(f,T) + P_{L,DC\_link}(f,T)\\ &+ P_{L,choke}(f,T) + P_{L,control}(f,T)\\ &+ P_{L,cooling}(f,T)\end{aligned} \tag{34}$$

$$P_{L,CDM,Relative}(f,T) = \frac{P_{L,CDM}(f,T)}{S_{r,out}} \tag{35}$$

IEC 61800-9-2 [4] provides a table with RCDM relative losses for all typical CDM power ratings and for the 8 pre-defined operating points (f,T). RCDM relative losses are associated with IE1 efficiency class and the threshold for class determination are defined as following:

- A CDM shall be classified as IE1 if its $P_{L,CDM}(90\%, 100\%)$ is within +/- 25% of the RCDM value.
- A CDM shall be classified as IE0 if its $P_{L,CDM}(90\%, 100\%)$ is more than 25% higher than the RCDM value (less efficient).
- A CDM shall be classified as IE2 if its $P_{L,CDM}(90\%, 100\%)$ is more than 25% lower than the RCDM value (more efficient).

The European Regulation (EU) 1781/2019 [2] defines, from 1 July 2021, the power losses of variable speed drives rated for operating with motors with a rated output power equal to or above 0.12 kW and equal to or below 1000 kW shall not exceed the maximum power losses corresponding to the IE2 efficiency level.

C. Power Drive System (PDS)

The PDS losses are the summation of CDM losses and motor losses at each operating point.

At any combination of frequency and torque, the PDS losses determination shall be done by Equation 36. However, PDS losses at rated condition (100% speed, 100% torque) is determined according to Equation 37 by using the 90% frequency and 100% torque point of the CDM and the 100% speed and 100% torque point of the motor multiplied by a correction factor k_{VD}.

$$P_{L,PDS}(f,T) = P_{L,CDM}(f,T) + P_{L,M@CDM}(f,T) \tag{36}$$

$$\begin{aligned}&P_{L,PDS}(100\%, 100\%)\\ &\qquad = P_{L,CDM}(90\%, 100\%)\\ &\qquad + k_{VD}\,.P_{L,M@CDM}(100\%, 100\%)\end{aligned} \tag{37}$$

The 90% frequency (90% voltage) point of the CDM is used to avoid overmodulation, which would appear for 100% frequency (100% voltage). Overmodulation decreases CDM loss but increases motor harmonic loss, this perturbance is not desirable to be added on PDS losses accountability.

Overmodulation happens to compensate the voltage drop in the internal electric switches of the CDM and to ensure full voltage and full magnetic flux to the motor. By limiting the CDM output voltage to 90% is similar to have a drop on the magnetic flux of motor in 10%. Therefore, the fundamental losses of the motor increase with a correction factor of $k_{VD} = 1.11$ (based on 10% voltage drop calculation).

A table with relative losses of reference PDS (RPDS) is also provided by standard IEC 61800-9-2 [4] for all typical PDS power ratings. The table is based on the application of equations 36 and 37, summing up the relative losses of RCDM and RM (reference motor).

RPDS relative losses are associated with IES1 efficiency class and the threshold for class determination are defined as following:

- A PDS shall be classified as IES1 if its $P_{L,PDS}(100\%, 100\%)$ is within +/- 20% of the RPDS value.
- A PDS shall be classified as IE0 if its $P_{L,PDS}(100\%, 100\%)$ is more than 20% higher than the RPDS value (less efficient).
- A PDS shall be classified as IE2 if its $P_{L,PDS}(100\%, 100\%)$ is more than 20% lower than the RPDS value (more efficient).

By the time this dissertation is written, there is none current regulation in force for PDS efficiency limits.

D. Driven Equipment

In this dissertation the driven equipment is considered as an axial fan coupled to a gearbox.

A fan as defined in Regulation 327/2011 [5] means a configuration of at least an impeller, stator and motor. These significant elements are required for continuous conversion of electrical power into air volume flow rate and pressure [8].

Fans convert the mechanical power (shaft torque) supplied by an electric motor through the gearbox into gas power. According to Commission Regulation (EU) 327/2011 [5], the fan gas power is calculated according to the measurement category test method chosen by the fan supplier:

TABLE II
FAN GAS POWER DETERMINATION

Category	Composition
A	Free inlet and outlet
B	Free inlet and with a duct fitted to its outlet
C	Duct fitted to its inlet and with free outlet
D	Duct fitted to its inlet and outlet

The Regulation (EU) 327/2011 [5] establishes a methodology to determine the overall fan system efficiency.

$$\eta_{overall} = \eta_{fan}\cdot \eta_{PDS@OP}\cdot \eta_{gearbox}\cdot C_m\cdot C_c \tag{38}$$

Where C_m is a compensation factor to account the components (mis)matching and C_c is a part load compensation factor when motor is driven by VSD.

The minimum energy efficiency requirement for axial fans in the range 125 W to 500 kW is set by Commission Regulation (EU) 327/2011 [5]. Since January 1st 2015 the limits of Table III are valid for axial fans.

TABLE III
MINIMUM ENERGY EFFICIENCY REQUIREMENT FOR FANS

Category	Power Range P (kW)	Target Efficiency η_{target}	Grade (N)
A, C	$0.125 \leq P \leq 10$	$2.74.\ln(P) - 6.33 + N$	40
	$10 < P \leq 500$	$0.78.\ln(P) - 1.88 + N$	
B, D	$0.125 \leq P \leq 10$	$2.74.\ln(P) - 6.33 + N$	58
	$10 < P \leq 500$	$0.78.\ln(P) - 1.88 + N$	

Where P is the PDS input power at fan operating point. The fan overall efficiency calculated according to the appropriate method must be equal to or greater than the target value set by the efficiency grade to meet the minimum energy efficiency requirements.

$$\eta_{overall} \geq \eta_{target} \tag{39}$$

IV. RESULTS

This chapter presents the outcoming results of the proposed methodology.

A. Electric Motor Calculated Efficiency

Table IV presents the electric motor data extracted from the manufacturer datasheet [9].

TABLE II
ELECTRIC MOTOR MANUFACTURER DATA

P_{mec}	132 kW
n_R	1486 rpm
$U_{r,in,M}$	400 V
$I_{r,in,M}$	229 A
$f_{r,M}$	50 Hz
$\eta_{M@DOL}$	95.6%
$R_{w(\Delta)}$@20°C	0.0345 Ω
$\cos\varphi_0$	0.04
U_0	400 V
I_0	53.8 A
s	0.0093

The methodology described in IEC 61800-9-2 [4] to compute part load losses in electric motors requires the previous knowledge of segregated losses. Motor's datasheet usually does not provide the segregated losses, only the total loss extracted from the rated efficiency.

Therefore, for this dissertation, the total loss at rated condition was segregated considering the Equations 4 to 11 as described by IEC 60034-2-1&3 [6] [7].

The segregated losses at rated condition is presented in Table V as Point 1 $(f, T) = (100\%, 100\%)$.

Based on the segregated losses at rated condition, the equations 12 to 22 were applied to compute the part load losses at points 2 to 8 as specified by IEC 61800-9-2 [4]. The results are also presented in Table V.

TABLE V
ELECTRIC MOTOR CALCULATED EFFICIENCY

Point	f	T	$P_{L,M@CDM}$	$P_{L,M,Relative}$	$\eta_{M@CDM}$
1	100%	100%	7594 W	5.8%	94.6%
2	100%	50%	4208 W	3.2%	94.0%
3	50%	100%	5714 W	4.3%	92.0%
4	50%	50%	3086 W	2.3%	91.4%
5	50%	25%	2429 W	1.8%	87.2%
6	10%	100%	4752 W	3.6%	73.5%
7	10%	50%	2511 W	1.9%	72.4%
8	10%	25%	1951 W	1.5%	62.8%

B. CDM Calculated Efficiency

The CDM manufacturer datasheet does not provide the constructive parameters to compute the losses as defined by IEC 61800-9-2 [4], the known information is resumed in Table VI.

TABLE VI
CDM MANUFACTURER DATA

λ	0.94
$I_{r,out,CDM}$	312 A
$U_{r,out,CDM}$	400 V
$S_{r,out,CDM}$	216 kVA
f_{sw}	2 kHz

From motor performance curve [9] it is possible to extract the motor absorbed current and displacement factor in function of relative load, which is resumed in Table VII.

TABLE VII
ELECTRIC MOTOR MANUFACTURER PERFORMANCE DATA

Load (%)	**100%**	**50%**	**25%**
$\frac{I_{in,M@OP}}{I_{in,M}}$	1.00	0.52	0.39
$\cos\varphi_{M@OP}$	0.87	0.82	0.61

Other required parameters are not given by CDM manufacturer datasheet, therefore this dissertation considered two approaches:

1) First approach: calculation of CDM efficiency considering the typical parameters given by IEC 61800-9-2 [4]. Equations 23 to 35 were applied to compute the rated and part load losses as specified by IEC 61800-9-2 [4]. The results are presented in Table VIII.

TABLE VIII
CDM CALCULATED EFFICIENCY – FIRST APPROACH

Point	f	T	$P_{L,CDM}$	$P_{L,CDM,Relative}$	η_{CDM}
1’	90%	100%	4236 W	2.0%	97.9%
2’	90%	50%	1766 W	0.8%	98.2%
3	50%	100%	3290 W	1.5%	97.0%
4	50%	50%	1480 W	0.7%	97.3%
5	50%	25%	1047 W	0.5%	96.3%
6	10%	100%	2759 W	1.3%	88.7%
7	10%	50%	1296 W	0.6%	89.3%
8	10%	25%	963 W	0.4%	84.9%

2) Second approach: CDM efficiency provided by the manufacturer [10], as presented in Table IX.

TABLE IX
CDM EFFICIENCY – SECOND APPROACH

Point	f	T	$P_{L,CDM}$	$P_{L,CDM,Relative}$	η_{CDM}
1’	90%	100%	2446 W	1.1%	98.3%
2’	90%	50%	1395 W	0.7%	98.1%
3	50%	100%	2085 W	1.0%	97.1%
4	50%	50%	1245 W	0.6%	96.5%
5	50%	25%	930 W	0.4%	95.1%
6	10%	100%	1739 W	0.8%	90.2%
7	10%	50%	1099 W	0.5%	87.7%
8	10%	25%	848 W	0.4%	83.0%

C. PDS Calculated Efficiency

Table X and Table XI show the PDS calculated efficiency considering the first and the second approach of CDM efficiency determination, respectively.

TABLE X
PDS CALCULATED EFFICIENCY – FIRST APPROACH

Point	f	T	$P_{L,PDS}$	$P_{L,PDS,Relative}$	η_{PDS}
1	100%	100%	12665 W	9.6%	91.2%
2	100%	50%	5974 W	4.5%	91.7%
3	50%	100%	9004 W	6.8%	88.0%
4	50%	50%	4566 W	3.5%	87.8%
5	50%	25%	3476 W	2.6%	82.6%
6	10%	100%	7511 W	5.7%	63.7%
7	10%	50%	3807 W	2.9%	63.4%
8	10%	25%	2914 W	2.2%	53.1%

TABLE XI
PDS CALCULATED EFFICIENCY – SECOND APPROACH

Point	f	T	$P_{L,PDS}$	$P_{L,PDS,Relative}$	η_{PDS}
1	100%	100%	10875 W	8.2%	92.4%
2	100%	50%	5603 W	4.2%	92.2%
3	50%	100%	7799 W	5.9%	89.4%
4	50%	50%	4331 W	3.3%	88.4%
5	50%	25%	3359 W	2.5%	83.1%
6	10%	100%	6491 W	4.9%	67.0%
7	10%	50%	3610 W	2.7%	64.6%
8	10%	25%	2799 W	2.1%	54.1%

D. Axial Fan Calculated Efficiency

Fan operating point is provided by the fan manufacturer as 120 kW at 50 Hz. Hence the load operating point is $(f, T) = (100\%, 91\%)$.

PDS efficiency at operating point is found according to proposed method.

Considering the fan test method category A and input power within the range 10 to 500 kW leads to an Efficiency Grade N = 40 and a target efficiency as defined by Table III. By knowing that fan overall efficiency shall be at least equal to η_{target}, it was possible to find the minimum axial fan efficiency to comply with Commission Regulation (EU) 327/2011. Results are presented in Table XII.

TABLE XII
AXIAL FAN CALCULATED EFFICIENCY

	First Approach	**Second Approach**
f	100%	100%
T	91%	91%
$\eta_{M@CDM}$	94.6%	94.6%
η_{CDM}	98.0%	98.9%
η_{PDS}	92.0%	92.4%
$P_{in,CDM}$	130.4 kW	129.9 kW
η_{target}	41.92%	41.92%
$\eta_{overall}$	≥ 41.92%	≥ 41.92%
η_{fan}	≥ 49.67%	≥ 49.47%

E. Comparison Between Calculated and Reference Losses

Electric motor has 18% less losses at rated condition than the reference motor specified by IEC 61800-9-2 [4], considering losses based on calculated values.

This result was expected as the reference motor is based on an IE2 efficiency class motor (94.7% at DOL condition) and the motor under analysis is an IE3 class motor (95.6% at DOL condition).

The comparison between calculated and reference losses for the CDM is shown in Table XIII, considering the two approaches of CDM losses determination.

TABLE XIII
CDM COMPARISON BETWEEN CALCULATED AND REFERENCE LOSSES

Point	***f***	***T***	$\frac{P_{L,CDM,Relative}}{P_{L,RCDM,Relative}}$	
			First Approach	**Second Approach**
1'	90%	100%	48%	28%
2'	90%	50%	41%	33%
3	50%	100%	52%	33%
4	50%	50%	40%	34%
5	50%	25%	37%	33%
6	10%	100%	58%	36%
7	10%	50%	40%	34%
8	10%	25%	37%	33%

This result gives the CDM the efficiency classification of IE2, as the calculated loss at rated condition is more than 25% lower than the RCDM value (more efficient), in both approaches.

The comparison between calculated and reference losses for the PDS is shown in Table XIV, considering the two approaches of CDM losses determination.

TABLE XIV
PDS COMPARISON BETWEEN CALCULATED AND REFERENCE LOSSES

Point	***f***	***T***	$\frac{P_{L,PDS,Relative}}{P_{L,RPDS,Relative}}$	
			First Approach	**Second Approach**
1	100%	100%	75%	64%
2	100%	50%	71%	66%
3	50%	100%	83%	72%
4	50%	50%	75%	71%
5	50%	25%	75%	73%
6	10%	100%	95%	82%
7	10%	50%	90%	85%
8	10%	25%	88%	85%

This result gives the PDS the efficiency classification of IES2, as the calculated loss is more than 20% lower than the RPDS value (more efficient), in both approaches.

F. Comparison Between Calculated and Measured Losses

To validate the methodology proposed to determine PDS efficiency, a 132 kW 4-pole IE3 400 VD 50 Hz electric motor and a 216 kVA 312 A VSD were tested together in a string test with input-output measurement setup as determined by IEC 61800-9-2 [4] and the measured losses were compared to the losses determined by the methodology.

Fig. 1 presents the comparison between motor calculated losses according to proposed methodology and the measured losses. The error is given as a proportion of measured result according to Equation 40.

$$Error = \frac{P_{L,Calculated} - P_{L,Measured}}{P_{L,Measured}}.100\% \qquad (40)$$

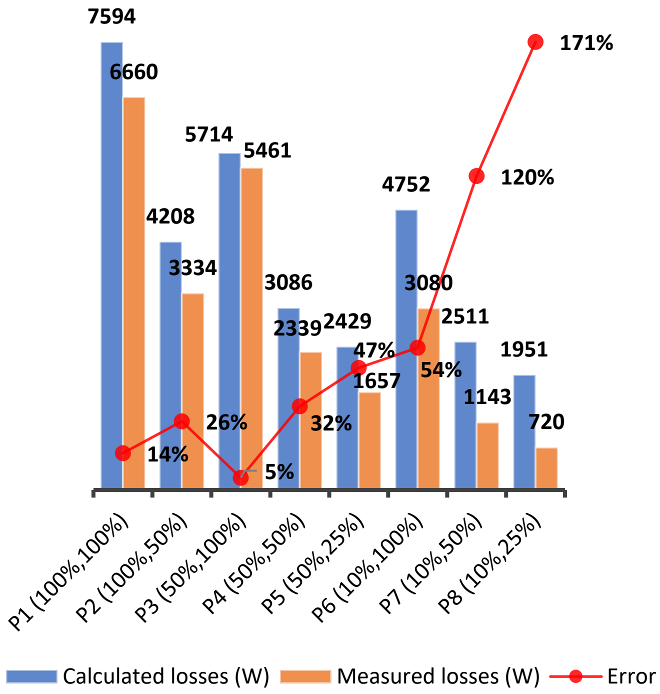

Fig. 1. Comparison between calculated and measured losses – Electric Motor

Motor's losses with direct on line supply were also measured to validate the datasheet values. It can be concluded that part of the error is due to the differences between the datasheet provided losses and the motor real losses at DOL supply, being the datasheet more conservative. At rated condition, 325 W out of 934 W error is due to this issue (or 5% out of 14% error).

The remaining part of the error is due to the harmonic losses that have been calculated at its maximum value as neither IEC 61800-9-2 [4] nor IEC 60034-2-3 [7] give any procedure to estimate the real harmonic losses, it represents approximately 9% of the error (609 W) out of 14% at rated condition.

As harmonic calculated loss for rated condition was carried with its constant value to the part load conditions, the error is more representative in part load points because other losses are much lower. This is the possible justification for errors in Points 2, 4 and 5 as the remaining absolute error are approximately the same for all of those (respectively 745 W, 538 W and 659 W). The Point 3 is divergent and could be a punctual measurement error.

Points 6, 7 and 8 with 10% frequency present the highest errors. At these points, the frequency is much lower than the rated frequency, so is the voltage applied at motor terminals.

As harmonic losses are produced in the motor by the non-sinusoidal voltage waveform generated by the converter, it could be possible that at lower voltages also lower harmonic losses are produced in the motor and, if that is true, the model could be overestimating the harmonic losses at lower frequency points by considering it constant on the whole operating zone.

Fig. 2 and Fig. 3 present the comparison between CDM measured losses and CDM calculated losses according to proposed methodology, considering the two approaches, respectively.

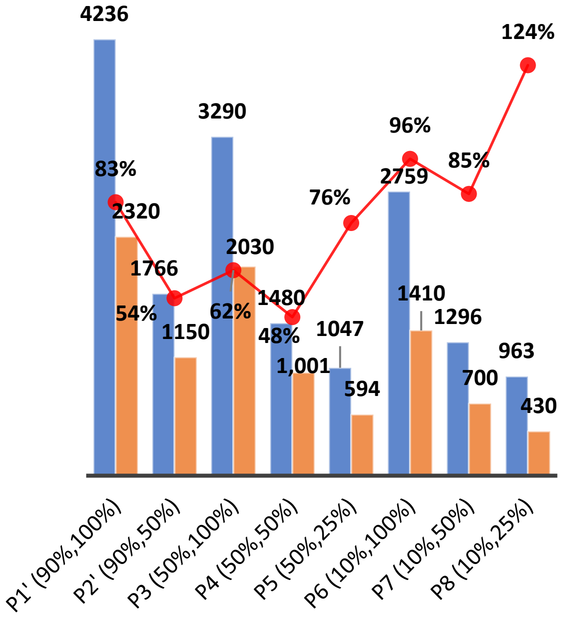

Fig. 2. Comparison between calculated and measured losses – CDM first approach

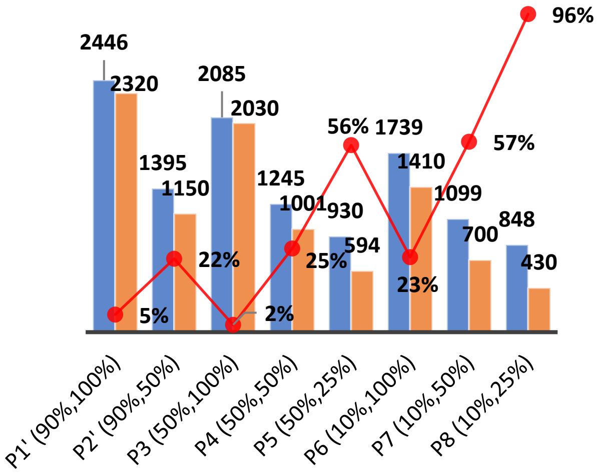

Fig. 3. Comparison between calculated and measured losses – CDM second approach

Graphs in Fig. 2 and Fig. 3 are presented in the same Y-axis scale for better representation.

As expected, the first approach presents higher error level than the second approach, as the latter considers the parameters of a real CDM while the former considers typical ones.

Usually calculated data are conservative as it includes testing uncertainties known by each manufacturer. Points 1 and 3 of Fig. 3, with 5% and 2% errors respectively, present good calculating results as these low error level probably represents the testing uncertainty. The errors presented in other points are not possible to be commented as it is unknown the method used to compute the part load losses provided by the manufacturer. However just by analyzing Fig. 3 it is clear that the errors increase when torque reduces and there is an additional error carried on Points 6, 7 and 8 where the frequency is at minimum. This tendency is not seen on Fig. 2, which makes the proposed methodology inaccurate as it should at least present the same trend. The additional error at 10% frequency (5 Hz) can be explained by the converter instability that occurs at very low frequencies, which is the reason why the standard IEC 61800-9-2 [4] allows measurement tolerance up to 12 Hz on Points 6, 7 and 8.

Fig. 4 and Fig. 5 present the comparison between PDS measured losses and PDS calculated losses according to proposed methodology, considering the two approaches, respectively.

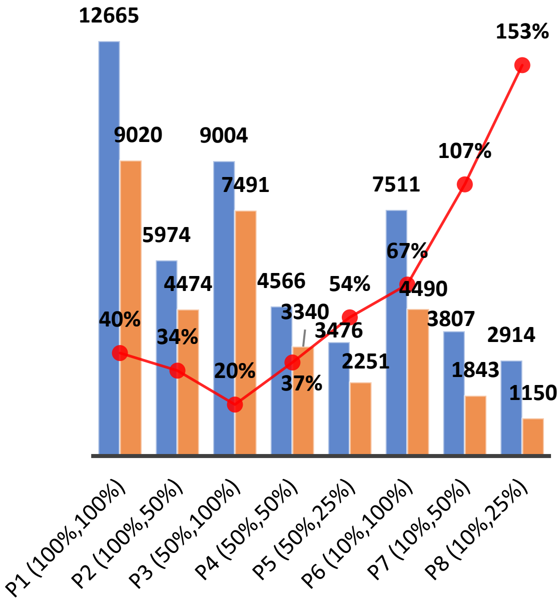

Fig. 4. Comparison between calculated and measured losses – PDS (CDM first approach)

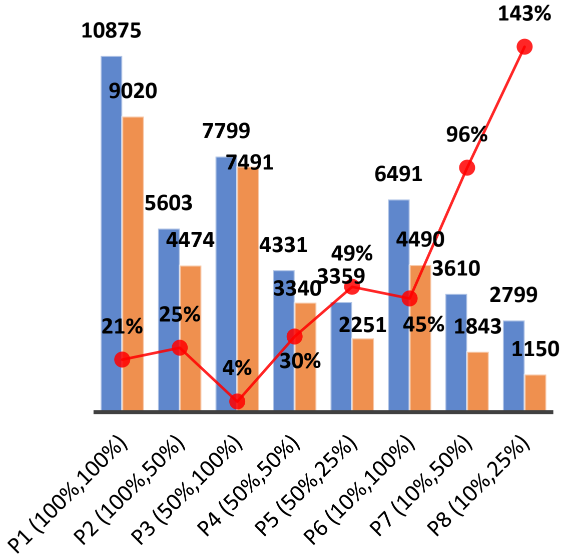

Fig. 5. Comparison between calculated and measured losses – PDS (CDM second approach)

Graphs in Fig. 4 and Fig. 5 are presented in the same Y-axis scale for better representation.

The PDS errors are the consequence of summing motor and CDM errors, therefore the error's analysis made for motor and CDM are also valid for PDS.

Fig. 4 shows that the high errors from CDM first approach calculation are attenuated due to their low representativity in PDS absolute loss values, as the motor absolute losses weight more than the CDM's. However, the expected error trend is still not seen, making the first approach feasible only as a rough approximation.

Fig. 5 presents lower errors, particularly at points 1 to 3. The Point 1 could have presented a better result, but the motor losses computation is majored by the correction factor k_{VD} according to Equation 37. If this factor were not considered, the error at Point 1 would be 11%.

V. CONCLUSION

A. *Specific Conclusion*

Standard IEC 61800-9 [3] [4] is a complete analysis of the Extended Product composed of an electric motor, a CDM, and a driven machine.

The author proposed to apply the Semi-Analytical-Model presented by IEC 61800-9-2 [4] to a real PDS, composing of an AC three-phase squirrel cage electric motor 132 kW 4-pole IE3 400 VD 50 Hz [9] and a stand-alone VSD 216 kVA 312 A 400 VD 50 Hz [10], with input data provided by the manufacturer datasheets, and validate the proposed methodology by comparing the calculated losses to the tested measured losses.

As a result, the author was able to compute the losses with the proposed methodology, however with certain difficulties:

- To compute the motor losses at part load condition it is required a previous knowledge of the segregated losses at rated condition, but that is not usually provided by the manufacturer datasheet. Therefore, to overcome this problem, the author proposed to segregate the total rated losses based on standard IEC 60034-2-1&3 [6] [7].
- The CDM datasheet does not provide the relevant parameters for CDM losses calculation. To overcome this issue, the author proposed two approaches: compute the CDM losses based on typical parameters provided by IEC 61800-9-2 [4] and use the CDM losses provided by the manufacturer [10].

The comparison between calculated losses and measured losses on the real PDS exposed that the proposed method overestimates the losses on all 8 operating points.

For electric motor the calculation method presented an error of 14% at rated condition. The methodology was acceptable as it was possible to track the divergences. The overestimation errors are consequence of three main factors:

- Motor datasheet is conservative and present lower efficiency at DOL condition than what is observed in tests.
- Proposed methodology considers the harmonic losses at its maximum allowed value as neither the IEC 61800-9-2 [4] nor IEC 60034-2-3 [7] give any methodology to estimate the real harmonic losses.
- Proposed methodology considers the harmonic losses constant for the whole operating zone as it considers this loss depending only on the converter switching frequency that is kept constant.

For CDM the calculation method presented an error at rated condition of 83% and 5% in the first and second approach, respectively. In addition to the high error rate of the first approach, by comparing the errors at part load condition of first and second approaches led to a questionable validity of the first approach methodology as it was expected that the errors would follow the same trend of the second approach, which was based on the real experience of the manufacturer.

As the PDS losses depend on the summation of motor and CDM losses, the PDS errors are a result of the motor and CDM errors (40% and 21% at rated condition considering the first and second approach, respectively). The error at rated condition is majored by the correction factor k_{VD}.

B. *General Conclusion*

The Ecodesign standard IEC 61800-9 [3] [4] is an important guide to manufacturers rely on as it represents the equalized understanding of how to calculate and measure energy efficiency in Power Drive Systems and presents reference losses to determine the system's energy efficiency classification. In Europe, the reference losses are defined as the baseline for new products entering the market, creating competition among manufacturers to reach or exceed the minimum efficiency performance standard.

Although, this dissertation discussed that the practical application of the methodology described by IEC 61800-9 [3] [4] in real cases presents some difficulties as it tends to overestimate the losses by using constant maximum parameters and the results based on typical parameters present significant errors.

Nevertheless, IEC 61800-9 [3] [4] came to fill a gap that was missing of how to compute energy efficiency of electric motors driven by converters. Switching gradually the narrow view of regulating standalone products towards broader system energy efficiency policies, where there are much more room for improvement.

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SYMBOLS AND ABBREVIATED TERMS

P – active power (W)
S – apparent power (VA)
T – torque (Nm)
n – speed (rpm)
f – frequency (Hz)
s – slip (pu)
U – voltage (V)
I – current (A)
$\cos\varphi$ – power factor (motor) or displacement factor (CDM)
λ – power factor (CDM)
η – efficiency (%)
R – resistance (Ω)
P_L – losses (W)
m – modulation index (-)
k – correction factor (-)
C – compensation factor (-)

The following subscripts may be added to symbols to differentiate values:

M – Motor
RM – Reference Motor
CDM – Complete Drive Module
RCDM – Reference Complete Drive Module
PDS – Power Drive System
RPDS – Reference Power Drive System
DOL – direct on line
OP – operating point
in – input
out – output
mec – mechanical
0 – no-load
S – stator
w – warm
R – rotor
cte – constant
Fe – core
fw – friction and windage
Res – residual
L – load
H – harmonic
r – rated
sw – switching
T – transistor
D – diode
th – threshold
on – on state
rec – rectifier
VD – voltage drop