Feasibility of Ecodesign Standard IEC 61800-9

A real case study

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Abstract

The Ecodesign Standard IEC 61800-9 defines a method to calculate the energy efficiency of Power Drive Systems (Electric Motor and Complete Drive System) and Extended Product (Power Drive System and driven equipment). Electric Motors have already been subject to minimum energy performance regulations for several years, but the European Directive 1781/2019 that will come into force in 2021 is the first to also regulate the drive, based on the method defined by IEC 61800-9. The outcome expected out of this dissertation was the application of the methodology described by IEC 61800-9 in a real Power Drive System to compute the Energy Efficiency Index of a real Extended Product and perform the feasibility analysis of IEC 61800-9 on the point of view of the Power Drive System manufacturer. After completing this study, it was possible to conclude that the proposed methodology applied to a real Power Drive System overestimated the losses. The method presented acceptable results for the Electric Motor, but significant errors for the Complete Drive Module (CDM), particularly when using the typical CDM construction parameters provided by the standard. In general, the proposed methodology is a guide for manufacturers to determine energy efficiency of electric motors driven by converters and the reference losses of IEC 61800-9 are useful as a baseline for new products entering the market.

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

Resumo

A norma de *Ecodesign* IEC 61800-9 define um método para calcular a eficiência energética de Sistemas de Accionamentos Eletromecânicos (Motor Elétrico e Módulo Conversor Eletrónico de Potência) e de Produtos Estendidos (Sistema de Accionamento Eletromecânico e equipamento accionado). Os motores elétricos já têm sido sujeitos a regulamentações de desempenho energético mínimo há vários anos, mas a Diretiva Europeia 1781/2019 que entrará em vigor em 2021 é a primeira a regulamentar também o conversor, com base no método definido pela IEC 61800-9. O resultado esperado dessa dissertação era a aplicação da metodologia descrita pela IEC 61800-9 a um Sistema de Accionamento Eletromecânico real para calcular o Índice de Eficiência Energética de um Produto Estendido real e fazer a análise de viabilidade da IEC 61800-9 do ponto de vista do fabricante do Sistema de Accionamento Eletromecânico. Após a realização deste estudo, foi possível concluir que a metodologia proposta aplicada a um Sistema de Accionamento Eletromecânico real superestimou as perdas. O método apresentou resultados aceitáveis para o Motor Elétrico, mas erros significativos para o Conversor de Potência, particularmente ao usar os parâmetros construtivos típicos do CDM (*Complete Drive System*) fornecidos pela norma. De forma geral, a metodologia proposta é um guia para os fabricantes determinarem a eficiência energética de motores elétricos accionados por conversores e as perdas de referência da IEC 61800-9 são úteis como linha de base para novos produtos que entram no mercado.

Palavras-chave: *Ecodesign*, IEC 61800-9, Sistema de Accionamento Eletromecânico, Eficiência Energética, Sistema de Motores.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

ABNT	Associação Brasileira de Normas Técnicas
AC	Alternating Current
BAU	Business-As-Usual
BSD	Basic Drive Module
CDM	Complete Drive Module
COP21	21st Conference of Parties (2015 Paris Climate Conference)
DC	Direct Current
DOL	Direct on-line
EC	European Commission
EEI	Energy Efficiency Index
EP	Extended Product
EPA	Extended Product Approach
EPAct	US Energy Policy Act
EU	European Union
GDP	Gross Domestic Product
IA	Impact Assessment
IEC	International Electrotechnical Committee
IPC	In-plant Point of Coupling
IS	International Standards
ISO	International Organization for Standardization
LCC	Life Cycle Cost
MEPS	Minimum Energy Performance Standard
NBR	Norma Técnica Brasileira
NEMA	National Electrical Manufacturers Association
OECD	Organisation for Economic Co-operation and Development
OEM	Original Equipment Manufacturer
OP	Operating Point
PCC	Point of Common Coupling
PDS	Power Drive System
RCDM	Reference Complete Drive Module
RM	Reference Motor
RPDS	Reference Power Drive System
SAM	Semi-Analytic Model
TEAO	Totally Enclosed Air Over
VFD	Variable Frequency Drive
VSD	Variable Speed Drive

List of Symbols

Power

P_{Grid} – weighted average electrical power supplied by the grid (W)
P_i – electrical power related to the operating point i supplied by the grid (W)
$S_{in,M}$ – motor input apparent power (V.A)
$P_{in,M}$ – motor input active power (W)
$Q_{in,M}$ – motor input reactive power (W)
P_{mec} – motor output rated mechanical power (W)
P_0 – motor input no-load power (W)
$P_{mec@OP}$ – motor output mechanical power at load operating point (W)
P – motor output relative power (pu)
$P_{in,CDM}$ – CDM input active power (V.A)
$P_{out,CDM}$ – CDM output active power (V.A)
$S_{out,CDM}$ – CDM input apparent power (V.A)
$S_{out,CDM}$ – CDM output rated apparent power (V.A)
P_u – fan output gas power (computed with total pressure parameter) (W)
P_{us} – fan output static gas power (computed with static pressure parameter) (W)
P_e – motor input power if motor is DOL (W)
P_{ed} – CDM input power if motor is driven by a VSD (W)
P_a – fan input shaft power (W)

Losses

P_{LS} – stator winding losses (W)
$P_{LS\theta}$ – stator winding losses temperature corrected (W)
P_{LR} – rotor winding losses (W)
$P_{LR\theta}$ – rotor winding losses temperature corrected (W)
P_{LSR} – stator and rotor winding losses (W)
P_{Lcte} – constant losses (W)
P_{Lfw0} – friction and windage losses at no load (W)
P_{Lfw} – friction and windage losses at rated speed (W)
P_{LFe} – core losses (W)
P_{LRes} – residual losses (W)
P_{LL} – additional load losses (W)
P_{LH} – additional harmonic losses (W)
$P_{L,M@DOL}$ – motor total losses at DOL supply (W)
$P_{L,M@CDM}$ – motor total losses at CDM supply (W)
$P_{L,M@CDM,Relative}$ – motor relative losses at CDM supply (pu)
$P_{L,on,T}$ – transistor ON state losses (W)
$P_{L,on,D}$ – freewheeling diode ON state losses (W)
$P_{L,sw,T}$ – transistor switching losses (W)
$P_{L,sw,D}$ – freewheeling diode switching losses (W)
$P_{L,inverter}$ – inverter losses (W)
$P_{L,rectifier}$ – rectifier losses (W)
$P_{L,choke}$ – choke losses (W)
P_{L,DC_link} – DC link losses (W)

$P_{L,rails}$ – rail losses (W)
$P_{L,control}$ – control and standby losses (W)
$P_{L,cooling}$ – cooling losses (W)
$P_{L,CDM}$ – CDM total losses (W)
$P_{L,CDM,Relative}$ – CDM relative losses (W)
$P_{L,PDS}$ – PDS total losses (W)
$P_{L,PDS,Relative}$ – PDS relative losses (W)
$P_{L,RM,Relative}$ – RM relative losses (W)
$P_{L,RCDM,Relative}$ – RCDM relative losses (W)
$P_{L,RPDS,Relative}$ – RPDS relative losses (W)
$P_{L,Calculated}$ – calculated losses (W)
$P_{L,Measured}$ – measured losses (W)

Time
Δt_i – time fraction of the operating point i (%)
ΔT – total runtime operation (h)

Torque
T_{mec} – motor output rated mechanical torque (N.m)
$T_{mec@OP}$ – motor output mechanical torque at load operating point (N.m)
T – motor output relative torque (pu)

Speed
ω_R – rotor rated rotational speed (rad/s)
n_R – rotor rated rotational speed (rpm)
$n_{R@OP}$ – rotor rotational speed at operating point (rpm)
n_S – rotor synchronous speed (rpm)
s – motor rated slip (pu)

Frequency
$f_{in,M}$ – motor input rated frequency (Hz)
$f_{in,M@OP}$ – motor input frequency at load operating point (Hz)
f – motor input relative frequency (pu)
f_{sw} – CDM switching frequency (Hz)
m – CDM modulation index (pu)

Efficiency
η_M – motor efficiency (%)
$\eta_{M@DOL}$ – motor efficiency at DOL supply (%)
$\eta_{M@CDM}$ – motor efficiency at CDM supply (%)
η_{CDM} – CDM efficiency (%)
η_{PDS} – PDS efficiency (%)
$\eta_{PDS@OP}$ – PDS efficiency at operation point (%)
η_e – overall efficiency of the fan impeller, transmission, electric motor, and VSD (if any) (%)
η_r – fan impeller efficiency (%)
η_T – transmission efficiency (%)

η_{target} – target efficiency of the fan impeller, transmission, electric motor, and VSD (if any) (%)

Energy

E_{Grid} – total electrical energy consumption (W.h)
E_T – transistor typical IGBT switching ON and OFF loss energy (J/V.A)
E_D – diode typical switching ON and OFF loss energy (J/V.A)

Current

$I_{in,M,Phase}$ – motor input phase current (A)
$I_{in,M,Line}$ – motor input line current (A)
$I_{in,M}$ – motor input rated current (A)
I_0 – motor input no-load current (A)
$I_{in,M@OP}$ – motor input current at load operating point (A)
$I_{in,CDM}$ – CDM input current (A)
$I_{1,in,CDM}$ – CDM input fundamental current (A)
I_{h5}, I_{h7}, I_{hn} – CDM input current at 5th, 7th and nth harmonic order (A)
$I_{out,CDM}$ – CDM output rated current (A)
$I_{out,CDM@OP}$ – CDM output current at load operating point (A)
I_{motor_cable} – additional current due to ohmic losses on cable between motor and CDM (A)

Voltage

$U_{in,M,Phase}$ – motor input phase voltage (V)
$U_{in,M,Line}$ – motor input line voltage (V)
$U_{in,M}$ – motor input rated voltage (V)
U_0 – motor input no-load voltage (V)
$U_{in,CDM}$ – CDM input voltage (V)
$U_{1,in,CDM}$ – CDM input fundamental voltage (V)
$U_{out,CDM}$ – CDM output rated voltage (V)
$U_{T,th}$ – transistor IGBT threshold voltage (V)
$U_{T,on}$ – transistor IGBT ON state voltage at CDM output rated current (V)
$U_{D,th}$ – inverter diode threshold voltage (V)
$U_{D,on}$ – inverter diode ON state voltage at CDM output rated current (V)
U_{DC} – DC link voltage (V)
$U_{D,th,rec}$ – rectifier diode threshold voltage (V)
$U_{D,on,rec}$ – rectifier diode ON state voltage at CDM input rated current (V)
U_{rails} – voltage drop at CDM to motor cables due to CDM output rated current (V)

Resistance

R_c – winding resistance at cold condition (Ω)
R_w – winding resistance at warm condition (Ω)
R_{Line} – line winding resistance (Ω)
R_{Phase} – phase winding resistance (Ω)
$R_{Phase(Y)}$ – phase winding resistance at Y connection (Ω)
$R_{Phase(\Delta)}$ – phase winding resistance at Δ connection (Ω)
$R_{Line(\Delta)}$ – line winding resistance at Δ connection (Ω)

Temperature

θ_c – winding temperature at cold condition (ambient temperature) (ºC)
θ_w – winding temperature at warm condition (ºC)

Power factor, displacement factor and harmonic distortion

φ – angle between current and voltage (rad)
$\cos\varphi_M$ – motor power factor (pu)
$\cos\varphi_0$ – motor no-load power factor (pu)
$\cos\varphi_{M@OP}$ – motor power factor at load operating point (pu)
$\cos\varphi_{in,CDM}$ – CDM input displacement factor (pu)
$\cos\varphi_{out,CDM}$ – CDM output displacement factor (pu)
λ – CDM power factor (pu)
$THDi$ – harmonic distortion on CDM input current (pu)
$THDv$ – harmonic distortion on CDM input voltage (pu)

Constants

n – quantity of operating points (-)
k_θ – temperature correction factor (-)
γ – linear regression correlation coefficient (-)
r_H – additional harmonic losses factor (-)
K_{Fe} – core losses constant (-)
K_{fw} – friction and windage losses constant (-)
K_{LL} – additional load losses constant (-)
$k1_{choke}$ – choke impedance, relative to the CDM rated impedance (-)
$k2_{choke}$ – relative voltage drop on the resistive part of the choke (-)
$k1_{DC\_link}$ – load independent DC link loss parameter $(\Omega\mathrm{A})^{-1}$
$k2_{DC\_link}$ – load dependent DC link loss parameter $(\Omega\mathrm{A})$
$k_{L,cooling}$ – cooling losses parameter at CDM rated condition (-)
k_{VD} – motor voltage drop correction factor (-)
k_{ps} – compressibility factor considering the fan static pressure
k_p – compressibility factor considering the fan total pressure
C_c – part load compensation factor if motor is driven by a VSD (-)
C_m – compensation factor to account the components (mis)matching (-)

Fan variables

q – volume flow rate (m³/s)
$\dot{m}$ – mass flow rate (kg/s)
ρ – gas density at inlet (kg/m³)
p_f – fan total pressure (Pa)
p_{sf} – fan static pressure (Pa)
V – gas axial velocity (m/s)

1. Introduction

The compromise to reduce CO_2 emissions directly imply in using more efficient electric equipment and systems. The Directive 2009/125/EC of the European Parliament and of the Council of 21 October 2009 [1] came into force to establish a framework for the setting of Ecodesign[1] requirements for energy-related products that represent significant volumes of sales and trade, have a significant environmental impact and present significant potential for improvement in terms of their environmental impact without entailing excessive costs.

Electric motors and the systems they drive are the single largest electricity end-use, consuming more than twice as much as lighting, the next largest end-use. According to a study made by IEA in 2011 [2], it was estimated that motor systems accounted for between 43% and 46% of all global electricity consumption, giving rise to about 6040 Mton of CO_2 emissions. By 2030, without any comprehensive and effective energy-efficiency policy measures, energy consumption from electric motors would be expected to rise to 13360 TWh per year and CO_2 emissions to 8570 Mton per year. When the research was done end-users spent USD 565 billion per year on electricity used in motor systems; by 2030, the bill could rise to almost USD 900 billion.

Since induction motors typically work for a large number of hours and have relatively long lifetimes, the greatest share of its environmental impact is in the use-phase. Hence, reducing motors' energy consumption, by increasing their efficiency, reduces their environmental impacts as well as their operational costs. The Figure 1 shows the result of a simple life cycle cost analysis (LCC) of a motor with 2000, 4000 and 6000 operating hours per year. This supports the fact that a higher initial purchase cost of a more efficient motor will, in fact, bring higher savings within short payback periods [3].

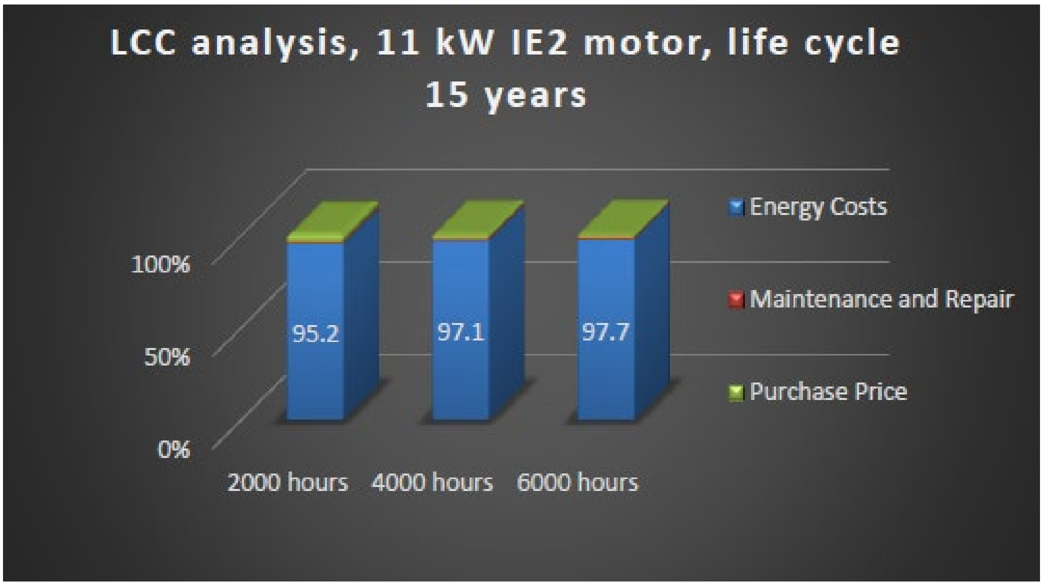

Figure 1 - Life cycle cost analysis for an electric motor 11 kW IE2 with life cycle 15 years [3]

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[1] '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 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. The Minimum Energy Performance Standard (MEPS) for electric motors in Europe was adopted on 22nd July 2009 as Commission Regulation (EC) 640/2009 [4]. More recently a new Commission Regulation (EU) 2019/1781 [5] was published, specifying more restricted energy efficiency requirements for electric motors, and adopting a Minimum Energy Performance also for variable speed drives (VSD). Regulation (EU) 2019/1781 [5] shall entry into force on 1st July 2021, date when Regulation (EC) 640/2009 [4] shall be repealed.

This is the first time that variable speed drives are subject to an energy efficient regulation. That is now possible with the advent of standard IEC 61800-9 Parts 1 and 2 from March 2017 [6] [7] that specifies Ecodesign requirements for Power Drive Systems, motor starters, power electronics and their driven applications. This standard defines an energy efficiency class for the Complete Drive Module (IE class) and the Power Drive System (IES class), as well as a Semi-Analytic Model (SAM) to calculate their efficiencies. Moreover, it defines an Extended Product Approach (EPA) to enable the driven equipment manufacturer to calculate its products overall Energy Efficiency Index (EEI).

1.1. Goals and structure 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 [6] [7] 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 [7] to compute the losses and efficiency of a real Power Drive System (PDS) at the operating points recommended by IEC 61800-9-1 [6].
- Comparison between motor, CDM and PDS calculated losses to their respective reference values given by IEC 61800-9-2 [7] 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. The divergences shall be discussed, and a feasibility analysis of the proposed methodology shall be made.
- 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.

This dissertation considers an AC asynchronous squirrel cage motor driven by a stand-alone variable speed drive as the Power Drive System, and an axial fan coupled to a gearbox as the driven equipment.

This dissertation is divided into the following chapters in addition to this introduction:

- Chapter 2 describes the context in which the Ecodesign directive was established and the need for action in public policy realm. A review of the motivations and goals of the standards and regulations regarding energy efficiency on electric motor systems is also presented.

- Chapter 3 presents the state of the art of Ecodesign on Power Drive Systems as described by IEC 61800-9 [6] [7] and introduces the concept of Extended Product Approach.
- Chapter 4 focus on the detailed description of the standardized IEC methodologies to compute energy efficiency of each component of the Extended Product as well as their efficiency class determination. The Semi-Analytic Model proposed by IEC 61800-9 [6] [7] to compute the efficiency on the point of operation of Power Drive Systems (electric motor and variable speed drive) is reviewed. Additional support from IEC 60034-2-1&3 [8] [9] standard is addressed to compute electric motors efficiency; and the method described in Annex II of Regulation (EU) 327/2011 [10] to compute the fan system efficiency (driven equipment) finally complements the study.
- Chapter 5 address the method proposed by the author to compute the energy efficiency of each part of the Extended Product and presents the calculation results from the proposed methodology. Calculated results are compared to the reference values given by IEC 61800-9-2 [7] and the CDM and PDS efficiency classes are determined. Calculated results are also compared to measured results to complete a feasibility analysis of the methodology.
- Chapter 6 finally presents the author’s conclusions based on the complete project implementation and future research recommendations.

2. Public policies for energy efficiency

Over the past decades much have been discussed about energy efficiency and sustainability, since it has been proved and internationally accepted that fossil fuels intensive industrial activities have direct interference on the global warming and consequently, on climate change. Figure 2 shows the global land and ocean temperature anomaly from 1880 to present and Figure 3 shows the fossil fuel related carbon dioxide emissions.

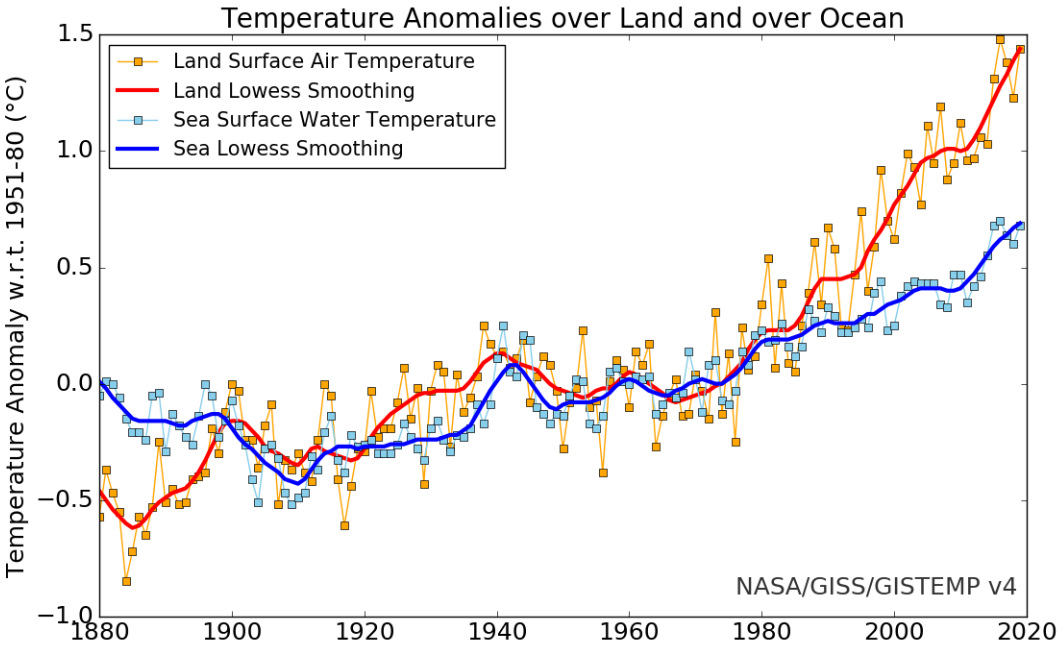


Figure 2 - Annual (thin lines) and five-year lowest smooth (thick lines) for the temperature anomalies (vs. 1951-1980) averaged over the Earth's land area and sea surface temperature anomalies (vs. 1951-1980) averaged over the part of the ocean that is free of ice at all times (open ocean) [11]

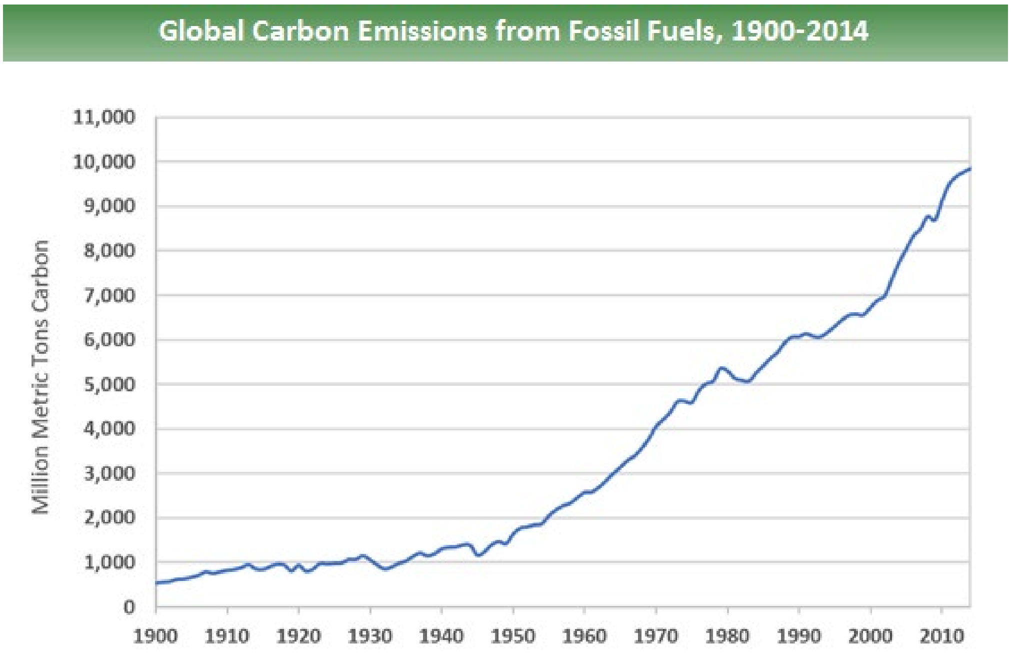


Figure 3 - Global carbon emissions from fossil fuels, 1900-2014 [12]

The worldwide recognition of global warming led to the first International Conference on the Environment in Rio in 1992 and some voluntary initiatives, standards, and guidelines all over the world. But it was on the Paris Agreement Conference (COP21) in December 2005 the first ever global deal signed by 195 countries to set a global level action plan to put the world on track to avoid dangerous climate change by limiting global warming to well below 2°C.

Most countries agreed on this global warming reduction plan, which has triggered to several actions on the majority industrial sectors and created a wave of investments and breakthrough innovations that has already profoundly transformed the global economy (and possibly also the society), what many authors characterize as a new technological revolution. According to Perez [13], technological revolution is defined as a major upheaval of the wealth-creating potential of the economy, opening a vast innovation opportunity space and providing a new set of associated generic technologies, infrastructures and organizational principles that can significantly increase the efficiency and effectiveness of all industries and activities.

Technological innovations play an essential role in solving current and future sustainability challenges. As the world population continues to increase, as well as world wealth and GDP per capita, more people will have access to the consumer market, demanding more production and consuming more energy.

However, this progressive movement was not a natural event. In general, societies are reluctant to breakthrough changes. Usually industry innovation drivers come from external sources, either the market pressure (customer requirements, which include cost reduction, higher quality, higher efficiency, etc.), or either legislation through public policies. Back in 2005, many barriers limited the market from demanding higher efficiency solutions and the industries to uptake them. The several barriers to implement energy efficiency solutions are presented in Table 1.

Table 1 - Classification of barriers to energy efficiency [2]

Theoretical Barriers	**Comment**
Imperfect information (Howarth and Andersson, 1993)	Lack of information may lead to cost-effective energy-efficiency measures opportunities being missed.
Adverse selection (Jaffe and Stavins, 1994)	If suppliers know more about the energy performance of goods than purchasers, the purchasers may select goods on the basis of visible aspects such as price.
Principal-agent relationships (Jaffe and Stavins, 1994)	Strict monitoring and control by the principal, since he or she cannot see what the agent is doing, may result in energy-efficiency measures being ignored.
Split incentives (Jaffe and Stavins, 1994)	If a person or department cannot gain benefits from energy-efficiency investment it is likely that implementation will be of less interest.
Hidden costs (Jaffe and Stavins, 1994)	Examples of hidden costs are overhead costs, cost of collecting and analyzing information, production disruptions, inconvenience, etc.
Access to Capital (Jaffe and Stavins, 1994)	Limited access to capital may prevent energy-efficiency measures from being implemented.

Risk (Jaffe and Stavins, 1994)	Risk aversion may be the reason why energy-efficiency measures are constrained by short pay-back criteria.
Heterogeneity (Jaffe and Stavins, 1994)	A technology or measure may be cost-effective in general, but not in all cases.
Form of information (Stern and Aronsson, 1984)	Research has shown that the form of information is critical. Information should be specific, vivid, simple, and personal to increase its chances of being accepted.
Credibility and trust (Stern and Aronsson, 1984)	The information source should be credible and trustworthy in order to successfully deliver information regarding energy-efficiency measures. If these factors are lacking, this will result in inefficient choices.
Values (Stern, 1992)	Efficiency improvements are most likely to be successful if there are individuals with real ambition, preferably represented by a key individual within top management.
Inertia (Stern and Aronsson, 1984)	Individuals who are opponents to change within an organization may result in overlooking energy-efficiency measures that are cost-effective.
Bounded rationality (DeCanio, 1993)	Instead of being based on perfect information, decisions are made by rule of thumb.
Power (Sorrell et al., 2000)	Low status of energy management may lead to lower priority of energy issues within organizations.
Culture (Sorrell et al., 2000)	Organizations may encourage energy-efficiency investments by developing a culture characterized by environmental values.

Due to these various imposed barriers, most countries decided not to wait for the market demand and took the energy efficiency topic to the legislative realm through public policies.

Public policy is an important tool to direct the market to what is understood as the most cost-effective for society in the long term and is not usually considered by the market agents. There are some positive externalities stemming from more energy efficient solutions not included on macroeconomic models and difficult to monetize, therefore policy makers must make the final trade-off between the models results and these ancillary benefits. Cost-benefit analyses for electricity considers the avoided investment on new power plants and the avoided external costs of conventional damage from electricity generation. However, the avoided external costs of climate change, for example, are still neglected, even in cost-benefit analyses that consider ancillary benefits [2].

A number of obstacles must be alleviated in order to realize the full potential of high-efficiency electric solutions. Therefore, only a portfolio of policy measures can serve this goal, as the obstacles must be removed simultaneously in the whole sector [2]. Public policies have always an open public involvement to create rules to which all the stakeholders are able to comply and make the target sector follow the expected direction. These policies are usually first released as a guideline or a list of good practices to later become a standard and consequently a mandatory regulation. As it may involve substantial sum of investment, the policy makers always establish a timeframe for the target companies prepare themselves. However, if after the deadline there will be still not-compliant companies, they shall simply be eliminated from the market, beneficiating most adapted companies, and eliminating completely the old fashion ones, what has some similarities with Darwin's natural selection theory.

According to Auer [14], standardization is the process of developing technical standards in mutual agreement of various stakeholders. Standardization enhances compatibility, interoperability, safety and quality and it can also facilitate commoditization of formerly custom processes. Therefore, the implementation of standards in industry and commerce became highly important with the onset of the Industrial Revolution and the need for high-precision machine tools and interchangeable parts.

In addition, International Standards (IS) provide a common language for the technical world, supporting global trade as a means of preventing technical barriers to trade due to national standards. Today there are mainly two well recognized international organizations, the ISO, the International Organization for Standardization, dealing with general standards and management systems, and the IEC, the International Electrotechnical Committee, which provides IS for all electrical, electronic, and related technologies [14].

In Europe, several actions and regulations on the public sphere have been implemented to comply with COP21 Agreement, particularly for those highly intensive energy use products, which actions are established as a framework on the Ecodesign Directive 2009/125/EC [1]. This Directive's goal is to achieve 20% annual energy savings by end of 2020 (when compared to the projected use of energy in 2020). In concrete terms, this means lowering the EU's final energy consumption to no more than 1078 Mtoe or primary energy consumption to no more than 1474 Mtoe (i.e. a reduction of 368 Mtoe as compared to projections) by end of 2020. This is roughly equivalent to turning off 400 power stations [15]. More recently the new Directive (EU) 2018/2022 [16] established the 2030 target of 32.5% annual energy savings, which means a reduction of 614 Mtoe of primary energy and 460 Mtoe of final energy consumption.

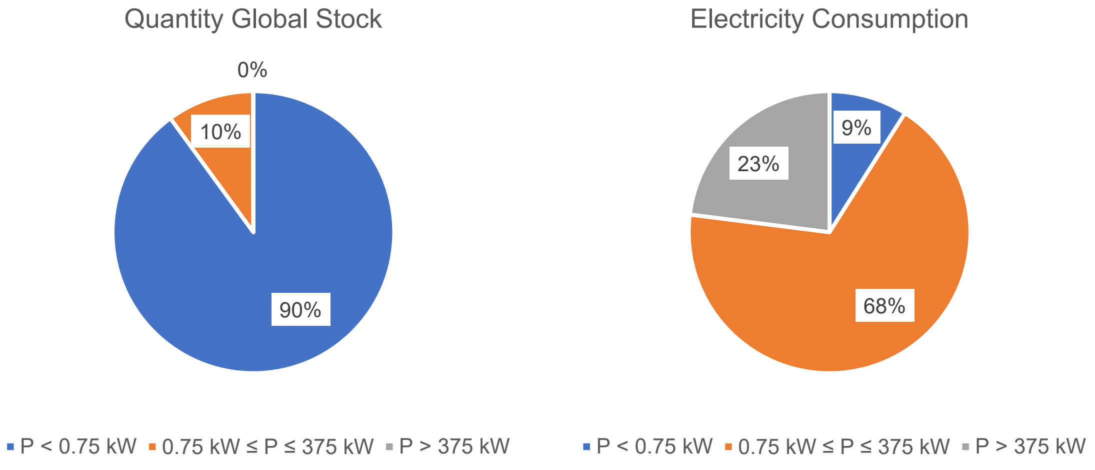
Electric motor systems were identified by the Ecodesign Directive as a key product group to be investigated, as it consumes nearly half of the whole electricity consumption in Europe. Consequently, Commission Regulation (EC) 640/2009 [4] with regard to Ecodesign requirements for electric motors was implemented with a view to regulate the motors with the largest saving potential.

According to IEA [2] study in 2011, the majority of electric motors in use draw less than 0.75 kW of power in a variety of small applications, mostly in the residential and commercial sectors. These motors account for about 90% of all electric motors in the global stock, but for only about 9% of the total electricity used by electric motors.

The largest proportion of motor electricity consumption is attributable to mid-size motors with output power of 0.75 kW to 375 kW, making them the target group of Regulation (EC) 640/2009. These motors account for about 10% of all motors in the global stock and for about 68% of the total electricity used by electric motors. Many different motor technologies and design types are available, but asynchronous AC induction motors are most frequently used and represent the majority of energy consumption. These motors are either sold to original equipment manufacturers (OEMs) and integrated into pre-packaged electromechanical products (such as pumps, fans, compressors, etc.) or sold as stand-alone motors to final customers then integrate into a specific application on site.

Large electric motors with more than 375 kW output power are generally high-voltage AC motors that are custom-designed, built to order, and assembled within an electromechanical system on site. They comprise just 0.03% of the electric motor stock in terms of quantity, but account for about 23% of all motor power consumption, making them very significant consumers of global power (about 10.4%).

Figure 4 presents the proportion of electric motors in quantity and electricity consumption.



(a) (b)

Figure 4 - Proportion of electric motors per output power: (a) quantity in global stock and (b) electricity consumption [2]

Figure 5 shows two Impact Assessments made for (EC) 640/2009 [17]. In the original 2009 Impact Assessment (IA1), about 140 TWh of annual energy savings were expected by 2020, and 208 TWh by 2030, compared to a Business-As-Usual situation (BAU - no regulation), representing saving of about 11% and 16% respectively. However, in 2019 a new Impact Assessment (IA2) was performed with more sophisticated modelling and updated hypotheses, leading to lower energy consumption on the BAU scenario and consequently lower savings. Nevertheless, the use of more efficient motors under the current regulation shall bring 57 TWh annual energy savings by end of 2020 and 102 TWh by 2030. This means that 40 million tons of CO_2 emission will be avoided each year and the annual energy bill of EU households and industries will be reduced by approximately € 20 billion by 2030, being fair to say that Regulation (EC) 640/2009 [4] has already transformed the motors market and delivered substantial savings.

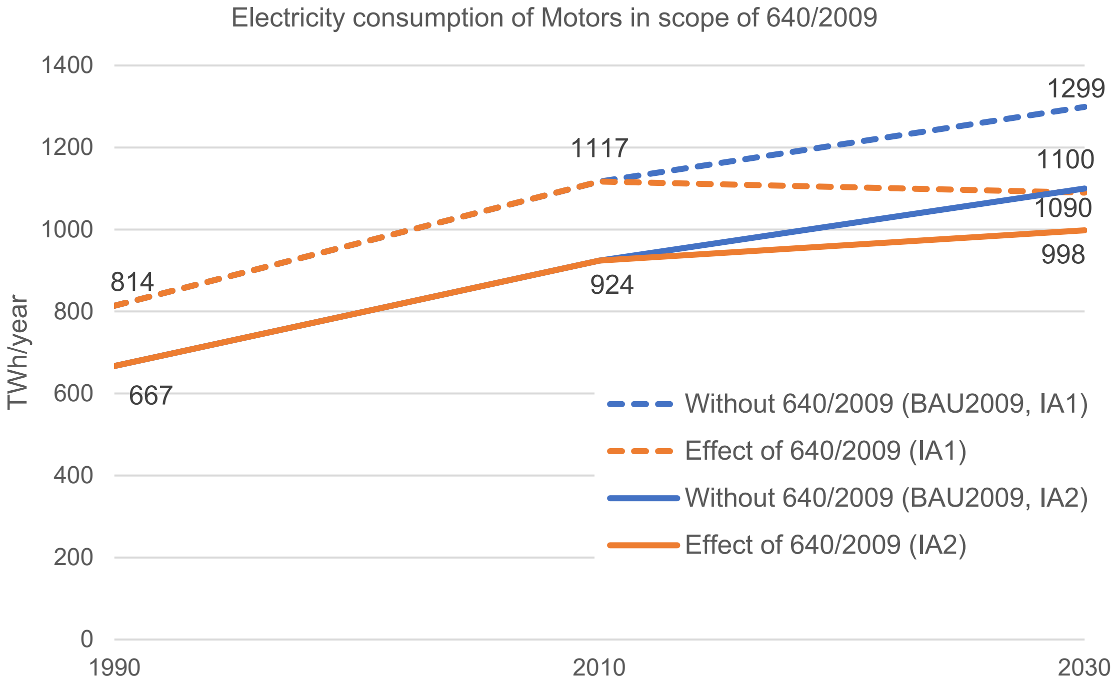


Figure 5 - Electricity consumption of motors in scope of Regulation (EC) 640/2009, comparison IA1 (2009) and IA2 (2017) [17]

According to Auer [14], United States was the leader country to promote the Minimum Energy Performance Standard (MEPS) for electric motors as a voluntary agreement approved by Congress in 1992 (US Energy Policy Act – EPAct 1992) to become effective in 1997. These higher efficient motors were first named EPAct motors and lately were incorporated as NEMA High Efficiency performance level in NEMA MG-1 standard.

Currently, the international standard IEC 60034 is the state of the art of electric motors performance. This standard was created with the first objective to avoid trade barriers for electric motors within the European market, but due to its completeness it has been spread to the majority of countries, being used either directly or converted into local standards with the same or partially the same requirements, for example the ABNT NBR 17094 standard in Brazil. The main exception is the National Electrical Manufacturers Association standard for Motors and Generators (NEMA MG-1), created in United States and followed by Canada, Mexico, and some other Latin American countries. NEMA MG-1 has the same purpose of IEC 60034 but uses different nomenclatures and specifies different requirements and tolerances.

When it comes to electric motors efficiency realm, the IEC 60034-2 [8] [9] specifies the several testing methods available to determine energy efficiency in electric motors. And the IEC 60034-30 [18] [19] specifies the efficiency classes based on reference values given for 50 and 60 Hz motors, the current edition of this standard presents the IE1, IE2, IE3 and IE4 efficiency classes and gives a brief introduction of what is expected for an IE5 class (20% loss reduction over IE4 reference values).

The IE classes for 50 Hz 4-pole motors according to IEC 60034-30-1 [18] is presented in Figure 6 and as an example, the minimum efficiency for each IE class of a 132 kW 4-pole 50 Hz motor is presented in Table 2.

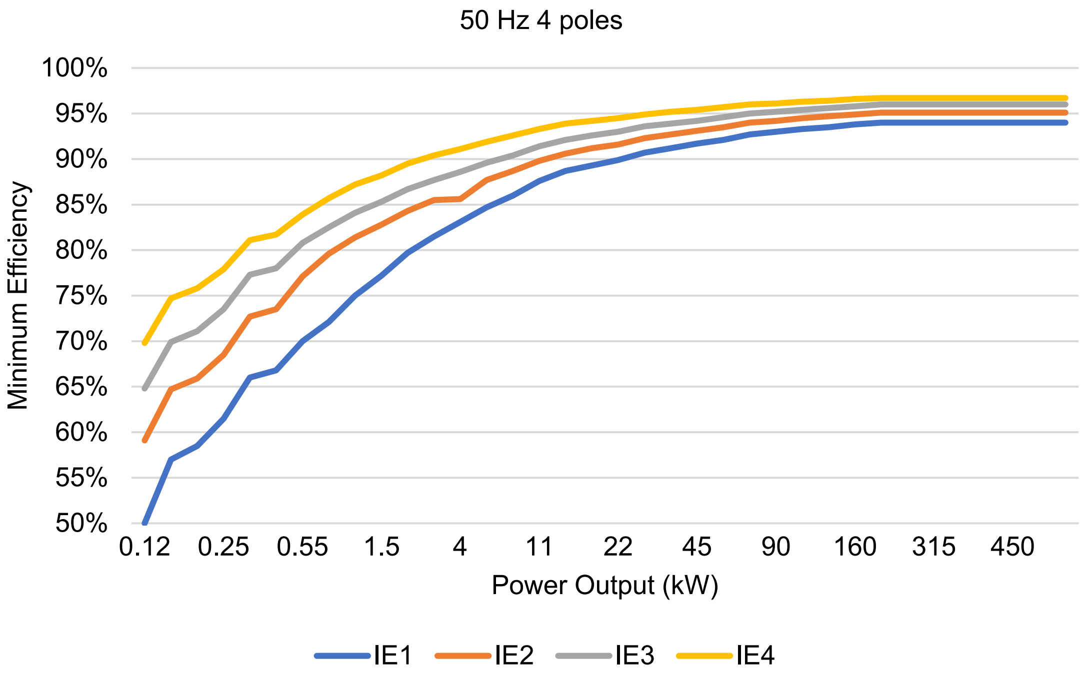


Figure 6 - IE classes for 50 Hz 4-pole motors [18]

Table 2 - Minimum efficiency for each IE class of a 132 kW 4-pole 50 Hz motor [18]

IE1	IE2	IE3	IE4	IE5 (estimated)
93.5%	94.7%	95.6%	96.4%	97.1%

Nowadays, many countries have already adopted a Minimum Energy Performance Standard themselves for the main class of industrial electric motors and many others are in the process of developing such requirements. One can say the EU started regulating the minimum energy efficiency of motors after many other economies, and its ambition levels are behind countries such as the USA, Japan, or Canada. Figure 7 shows the MEPS requirement in different countries and the entry into force year.

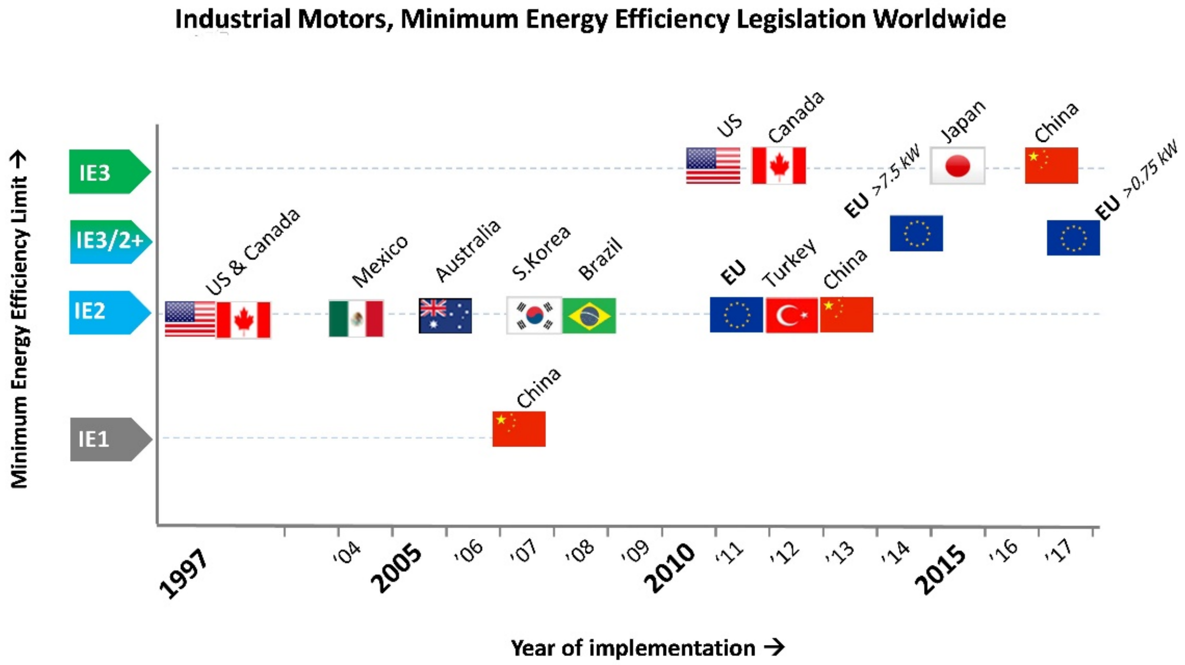


Figure 7 - Minimum energy efficiency legislation worldwide, status 2015 [17]

Different than electric motors, that have a broad literature and a complete testing performance standard, variable speed drives did not have an international standard to determine their efficiency before the release of IEC 61800-9 [6] [7] in 2017. The reason is mainly due to the fact that variable speed drives require an electric motor to be tested together and until the concept of Power Drive System has been clearly defined, the electrical committees allowed each drive manufacturer to decide on their own test methods.

Nevertheless, even without standardization, the efficiency of stand-alone variable speed drives is generally high due to its almost absence of resistive elements.

Examples of catalogue efficiency of stand-alone variable speed drives suitable for 132 kW 4-pole 50 Hz 400 V motor of different manufacturers are presented in Table 3.

Table 3 - Catalogue efficiency of VSD suitable for 132 kW 4-pole 50 Hz 400 V motor [20] [21] [22]

Manufacturer	WEG	ABB	Schneider
Model	CFW110242T4	ACS880-01-246A-3	ATV630C13N4
Rated current	242 A	246 A	250 A
Rated efficiency	98.0%	98.0%	97.7%

One can realize that rated efficiency is already considerable high for line fed electric motors and stand-alone variable speed drives, giving limited opportunity for improvement on these individual products. Thus, it is comprehensive that the standards committees would eventually migrate to the system efficiency focus, as there are more room for improvement in system installations than in each individual equipment.

The study made by IEA [2] presents this opportunity, it says that not only the electric motor should be addressed for regulation, but the complete motor system including its control and its driven equipment. According to this study, using the best available motors typically save about 4% to 5% of all motor systems energy consumption. Linking these motors with electromechanical solutions that are tailormade for the end-user can typically save another 15% to 25%. Therefore, the potential exists to improve energy efficiency of motor systems by roughly 20% to 30%, which could reduce total global electricity demand by about 10%.

According to the same study, the net mechanical energy used in motor system is estimated to be approximately 50% of the electrical energy input into the motor system. That is similar to say that electric motor systems operate at an efficiency of about 50%. The losses occur in the motors themselves as well as in throttles and dampers, gears, transmissions, clutches, brakes, power converters, etc.

Without a public policy intervention, many obstacles prevent the market from investing in more efficient electric motor systems solutions. Some of these barriers are common to other energy-using products that was exposed in Table 1, but others are unique to motor systems, as for example [2]:

- Lack of awareness among motor purchasers of the potential for energy and cost savings by using more efficient motors within energy-efficient system.
- Company organizational structures that manage their equipment procurement budget separately from operations and maintenance budgets.
- The fact that motors are often integrated into equipment produced by OEMs (Original Equipment Manufacturers) before sale to the final end-user.

The Ecodesign Directive for Power Drive System was written with the objective to give light to the energy savings potential of motor systems and guide manufacturers and purchasers towards the most efficient solutions. First it was published at regional level in Europe as EN 50598 Parts 1, 2 and 3 [23] [24] [25] published in December 2014, and later at international level as IEC 61800-9 Parts 1 and 2 [6] [7] in March 2017:

- IEC 61800-9-1: Adjustable speed electrical Power Drive Systems – Ecodesign for Power Drive Systems, motor starters, power electronics and their driven applications – General requirements for setting energy efficiency standards for power driven equipment using the extended product approach (EPA) and semi analytic model (SAM) [6].
- IEC 61800-9-2: Adjustable speed electrical Power Drive Systems – Ecodesign for Power Drive Systems, motor starters, power electronics and their driven applications – Energy efficiency indicators for Power Drive Systems and motor starters [7].

This standard addresses the complete Power Drive System which includes the motor itself and the Complete Drive Module. Moreover, it defines an Extended Product Approach to enable the driven equipment manufacturer to calculate its product overall Energy Efficiency Index. According to Auer [14], this is the first comprehensive and holistic Ecodesign standard for drive system developed in the context of standardization issued by the European Commission.

Driven equipment with high volume of trade and presenting significant potential for improvement in terms of their environmental impact also represent products for which the Directive 2009/125/EC [1] requirements should be established.

According to IEA [2], fans systems account for approximately 18.9% of electric motor-system energy consumption, and potential system improvements are estimated to be of the order of 40% in OECD countries, making them a high priority for the Ecodesign directive. With this regard, the Commission Regulation (EU) 327/2011 of March 2011 [10] implements the Ecodesign requirements for fans driven by motors with an electric input power between 125 W and 500 kW.

Further details about the Ecodesign requirements for motor systems are discussed in chapter 4 of this dissertation.

3. Ecodesign for Power Drive System – The Extended Product Approach

Energetic systems can be composed of different types of energy, named electrical, mechanical, kinetic, chemistry, etc. The way to compute efficiency is always the same, as output power divided by input power, even if the nature of each energy is different. The efficiency, therefore, is a parameter to compare different systems with the goal to determine the most economical one, the more efficient a system the less input is required to produce the same output. That is valid for all energetic systems regardless their nature.

Certainly, one can divide the system in sub-systems, compute the individual efficiency of each part, multiply all the individual efficiencies, and find the total system efficiency. The assumption that one single element of the system can be evaluated considering all the others invariable, named *ceteris paribus* assumption, is generally accepted in science due to the simplicity of dealing with direct related parameters at input and output and due to the impossibility of taking all parameters into consideration on calculation methods. Taking an electric motor and its axial fan load as an example, it is simpler to determine the efficiency of the motor and the axial fan separately: one can compute electric input power and mechanical output power of the motor to find motor efficiency, and fan input torque and output gas power to determine fan efficiency, then multiply both efficiencies to find the system efficiency. This is the currently used method, as each manufacturer is able to provide the efficiency of its own product alone.

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 [6] [7] 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. Figure 8 reproduces the system's parts described by the standard.

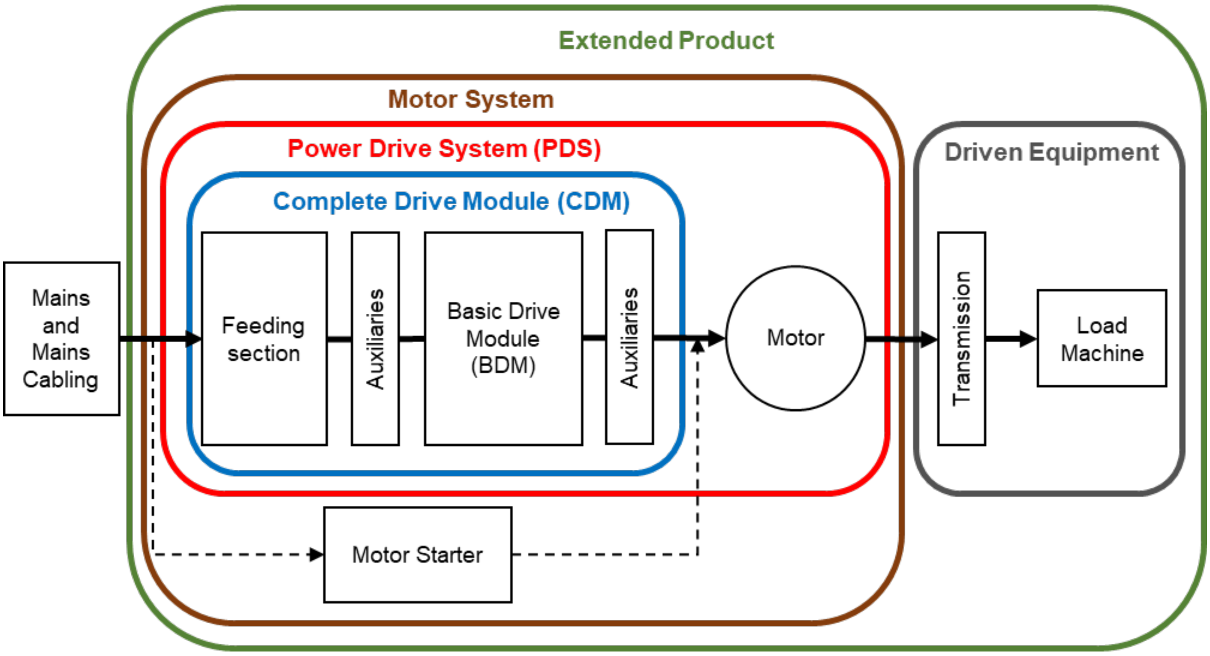


Figure 8 - Illustration of the extended product including a motor system [6] [7]

The parts of an Extended Product according to IEC 61800-9-1 [6] are following described:

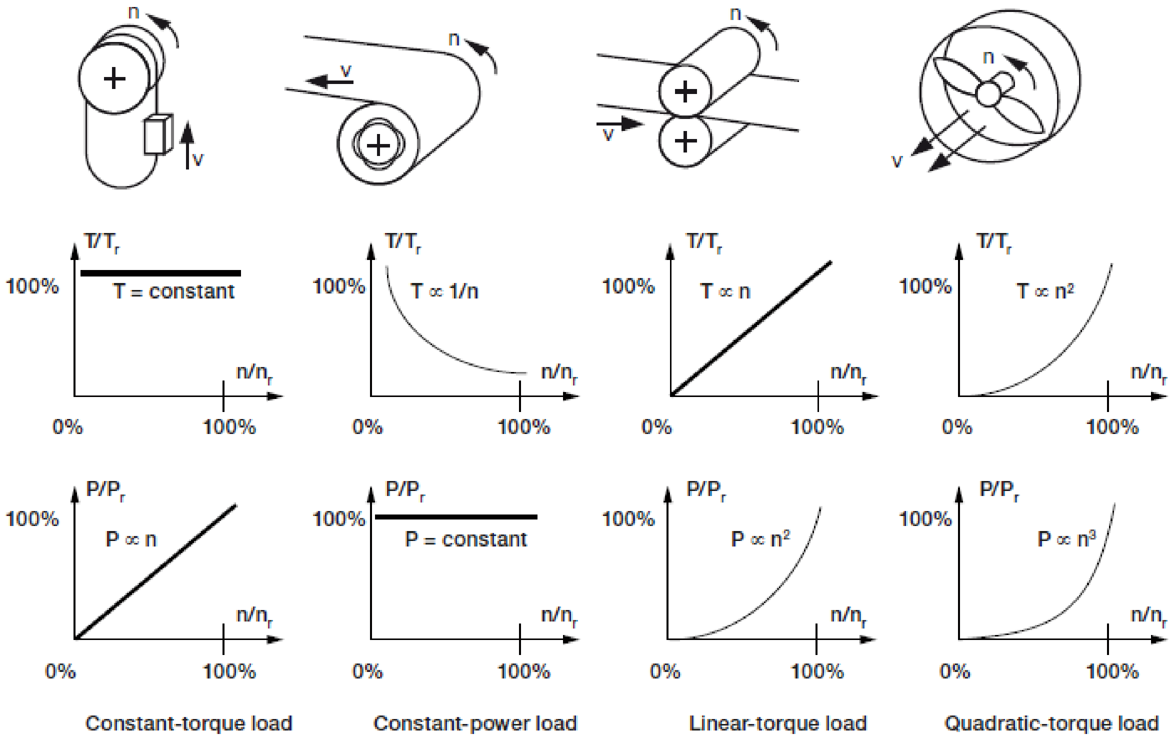
- Mains and cabling – the grid supply equipment as transformers, switchgears, etc. and cabling. These parts are out of the Extended Product.
- Complete Drive Module (CDM) – basic drive module (BDM) consisting of the electronic power converter, specifically the variable speed drive (VSD), connected between 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). Herein referred as motor or drive machine.
- 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. In addition, it is considered that energy flows from the grid to the load machine, which means that it disregards any sort of regenerative energy injected back to the grid. The study extension for regenerative drives, other motor starting methods or other load machines is reserved for future research.

The Extended Product Approach (EPA) described by IEC 61800-9 [6] [7] employs a Semi-Analytical Model (SAM) – 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.

There are a variety of machines that can be classified as driven equipment on the realm of IEC 61800-9 [6] [7], basically all machines that require any sort of movement to function may need a PDS to enable their movement.

These machines, regardless their transmission system, can be classified by their absorbed torque or power versus speed curve profile, which describes their load behavior seen from the motor shaft (the driver machine). Most of the existing loads can be categorized into one of the basic profiles shown in Figure 9.



Constant-torque load Constant-power load Linear-torque load Quadratic-torque load

Figure 9 - Typical torque and power versus speed curve profiles [6]

Typical examples of load machines according to torque profiles shown in Figure 9:

- Constant torque: conveyors, lift.
- Constant power: unwinder paper machine.
- Linear torque: roller mills.
- Quadratic torque: centrifugal pumps, fans, screw compressors.

The load torque/power versus speed curve has to match with motor torque/power versus speed curve itself on all operation points, in a way that motor available torque has to be equal or higher than the load absorbed torque at all speed range. As the motor curve profile is typically different than the load machine's, motors must be designed for the maximum absorbed torque and power of the load machine. Motors designed for the worst condition operate with idle capacity most of the time.

Partial load in the sense of IEC 60081-9 [6] [7] 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.

The efficiency reduction for partial load (torque and speed) are presented in Figure 10 for direct on-line motors, Figure 11 for stand-alone VSD and Figure 12 for PDS.

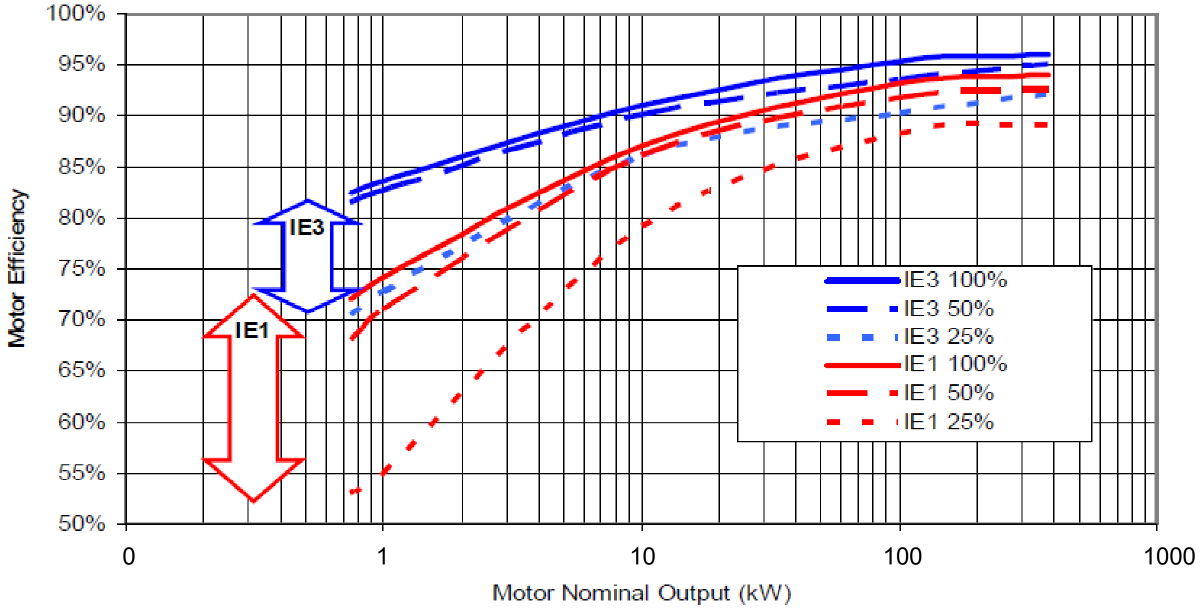


Figure 10 - Partial load efficiency of IE1 and IE3 4-pole motors [2]

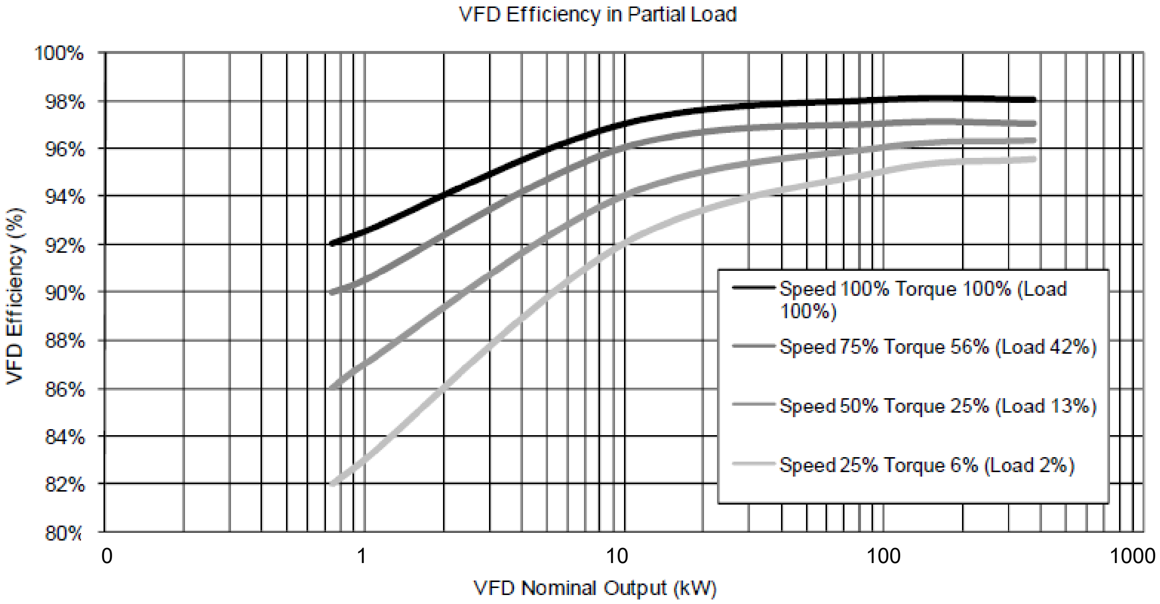


Figure 11 - VSD efficiency at full and partial load [2]

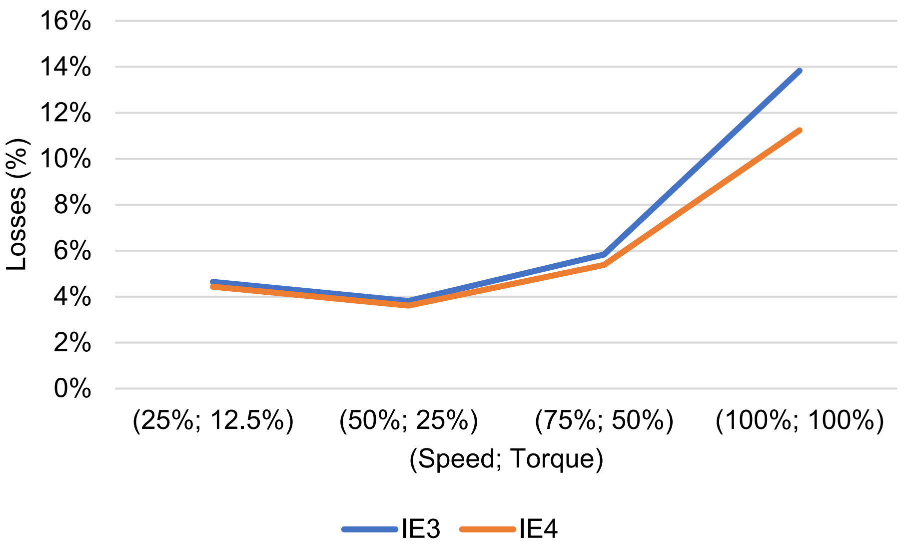


Figure 12 - PDS losses as a percentage of the output rated power for 7.5 kW 4-pole IE3 and IE4 motors [26]

Partial load implies additional losses for the Power Drive System, however these losses may be compensated by the load optimal point switch in quadratic load torque applications (fans, pumps, compressors, etc.).

Most fans applications operate with variable flow and pressure, which directly impacts on the fan absorbed power. While the fan flow is proportional to the speed, the fan pressure is related to the square of speed and the fan absorbed power to the third power of speed. What means that, for example, when the fan needs to deliver 50% of its rated flow, instead of using inefficient throats or valves solutions, the fan-motor-drive system can reduce its speed in 50%, so the fan absorbed power will decrease to approximately 12.5% of its original value, demonstrating the dramatic and inherent energy saving benefit of using a variable speed drive with intelligent control for fan applications. Figure 13 illustrates the fan related parameters.

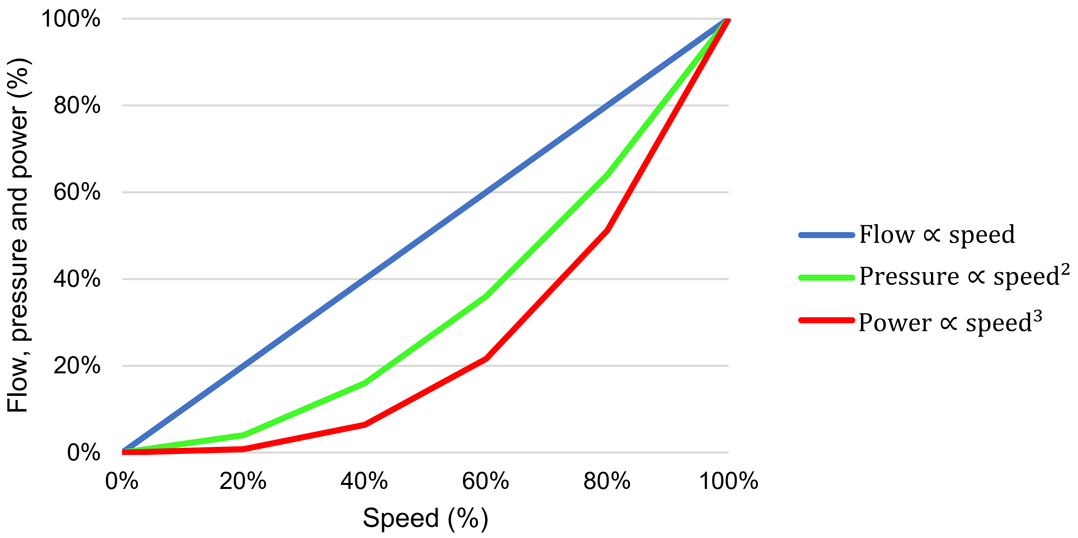


Figure 13 - Flow, pressure, and absorbed power relation to variable speed fan applications [27]

However, the speed control drive (VSD) always causes an additional loss to the fan-motor system, thus this technique should be applied only when the fan operates at partial load for long time, when the energy saving is higher than the additional loss. IEC 61800-9-1 [6] recommends computing the energy consumption of each feasible control solution to choose the most efficient one.

The typical load curves showed in Figure 9 are not enough data to evaluate the most efficient control technique of an Extended Product, as it is required a period of time to compute the energy consumption of each solution. Therefore, to complement the analysis it is necessary to evaluate the point of operation of the driven equipment over time, named the duty cycle. Figure 14 shows an example of several power levels required by a load machine, including standby, and the fraction of time during which this machine operates at each operating point (OP).

The operating points may be expressed as absorbed power or any other quantity that makes sense for the load machine, for example pressure, flow, velocity, etc. The time may be expressed in hours per unit of time (day or year) or in fraction of the total lifecycle.

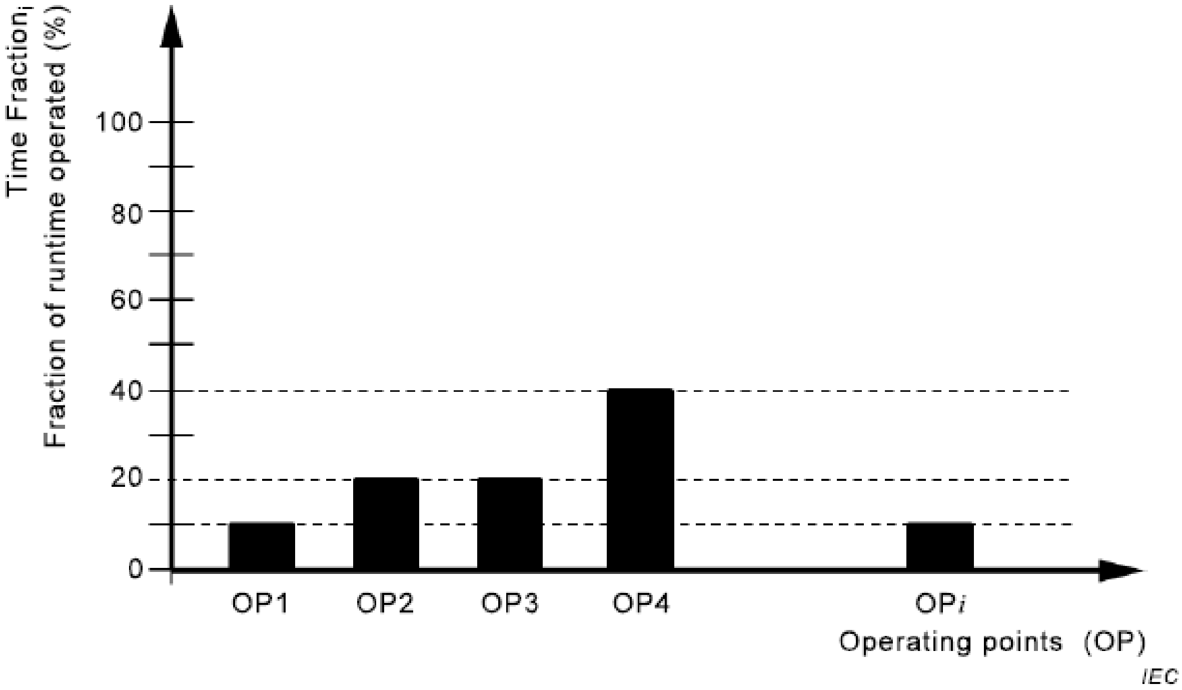


Figure 14 - Example of operating points over time (load machine duty cycle) [6]

For each operating point, regardless the parameter it represents, there is an associated electrical power that must be supplied by the grid, which includes the required mechanical power itself to run the load and the overall Extended Product losses at that OP. The latter depends on the control strategy chosen for the Extended Product, or in other words, it depends on the motor system chosen components: motor type and motor starting method (complete CDM, stand-alone VSD, softstarter, direct on-line motor, etc.).

The weighted average electrical power required to run the Extended Product as desired, including its overall losses, is given by Equation 1.

$$P_{Grid} = \sum_{i=1}^{n} (P_i . \Delta t_i) \tag{1}$$

The electrical energy consumption required by the chosen Extended Product during a certain period of time is given by Equation 2.

$$E_{Grid} = P_{Grid} . \Delta T \tag{2}$$

The designer should compare the several potential control strategies suitable for the Extended Product and select the control strategy that yields the smallest weighted average electrical power as it leads to the minimum energy consumption over time. This analysis shall be made calculating the Energy Efficiency Index as described by IEC 61800-9-2 [7].

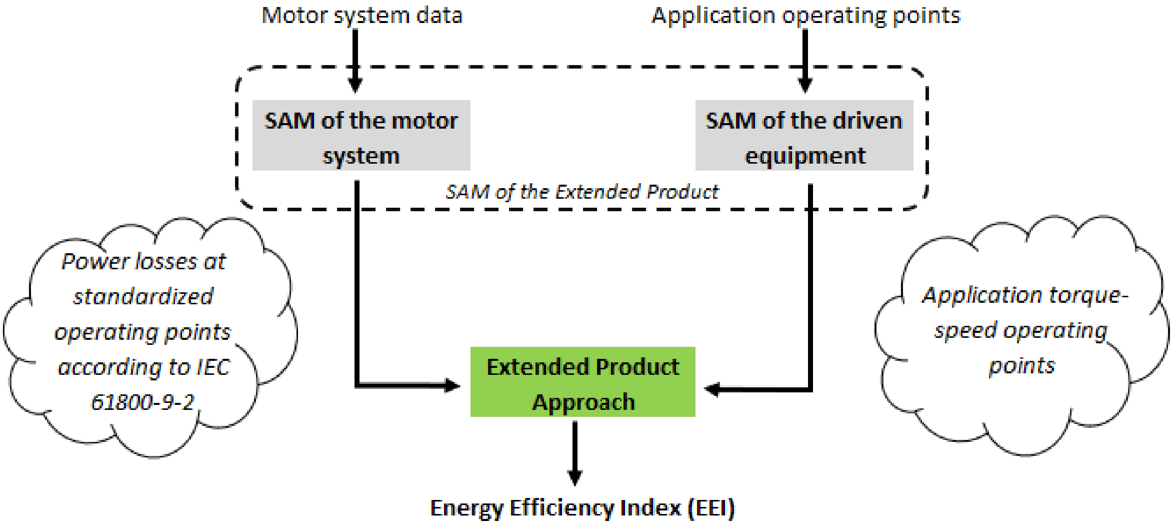


Figure 15 - Workflow to determine the Energy Efficiency Index of an Extended Product [7]

The IEC efficiency methodology review is presented in the next chapter of this dissertation, describing the SAM for each component of the Extended Product in order to apply them for the real case study.

4. IEC efficiency methodology review

4.1. Electric motor

Electric Motor is the electromechanical machine that converts electrical power into mechanical power. The electrical power absorbed by the motor is the apparent power supplied by the grid or by a CDM, designed by $S_{in,M}$. Apparent power consists of active power $P_{in,M}$ and reactive power $Q_{in,M}$. It is related by the Equation 3.

$$S_{in,M}^2 = P_{in,M}^2 + Q_{in,M}^2 \tag{3}$$

Apparent power is defined by Equation 4.

$$S_{in,M} = 3.U_{in,M,Phase}.I_{in,M,Phase} \tag{4}$$

Electric motors stator windings are either Y or Δ connected, in any of the cases the supplied apparent power is the same, as demonstrated by Equation 5.

$$\begin{aligned} &Y\ connection \rightarrow U_{in,M,Phase} = \frac{U_{in,M,Line}}{\sqrt{3}}\ ; I_{in,M,Phase} = I_{in,M,Line} \xrightarrow{yields} S_{in,M} = \sqrt{3}.U_{in,M,Line}.I_{in,M,Line} \\ &\Delta\ connection \rightarrow U_{in,M,Phase} = U_{in,M,Line}\ ; I_{in,M,Phase} = \frac{I_{in,M,Line}}{\sqrt{3}} \xrightarrow{yields} S_{in,M} = \sqrt{3}.U_{in,M,Line}.I_{in,M,Line} \end{aligned} \tag{5}$$

RMS line values of voltage and current are referred as the rated values in this dissertation, it is the voltage and current feasible to measure in the test bench. They are simplified by notation $U_{in,M}$ and $I_{in,M}$.

For a pure sinusoidal system (direct on-line motor), three-phase active and reactive power can be determined according to Equation 6.

$$\begin{aligned} P_{in,M} &= \sqrt{3}.U_{in,M,Line}.I_{in,M,Line}.\cos\varphi \\ Q_{in,M} &= \sqrt{3}.U_{in,M,Line}.I_{in,M,Line}.\sin\varphi \end{aligned} \tag{6}$$

Where φ is the angle between current and voltage. It defines if current is leading or lagging with related to the voltage. As electric motors are predominant inductive loads, the current is always lagging behind the voltage. And $\cos\varphi_M$ is also named the electric motor power factor.

The active power is the useful power that is effectively converted into mechanical power on motor shaft (deduced losses) and the reactive power is the absorbed additional power to create the magnetic field in the motor, even being considered a load to the upstream system, reactive power is essential because it is the responsible for the conversion phenomena itself.

The way to convert electrical energy into mechanical depend on an intermediary mean or agent, named the magnetic field. The magnetic field can be understood as an energy reservoir, supplying energy to the output mechanical system, and being replenished by the input electrical system through electric-magnetic field interactions [28].

Therefore, electric energy from the grid or from the CDM is converted into a sort of energy that is stored in the magnetic field of the machine. And the magnetic field interacts with the free-to-move parts of the motor (rotor) through mechanical force in order to reduce the reluctance path for the magnetic flux.

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

$$\begin{pmatrix} Electrical \\ Energy \end{pmatrix} = \begin{pmatrix} Mechanical \\ Energy \end{pmatrix} + \begin{pmatrix} Stored \\ Energy\ in\ the \\ Magnetic\ Field \end{pmatrix} + \begin{pmatrix} Heat \\ Losses \end{pmatrix} \tag{7}$$

Where:

$$\begin{pmatrix} Heat \\ Losses \end{pmatrix} = \begin{pmatrix} Joule \\ Losses \end{pmatrix} + \begin{pmatrix} Friction \\ Windage \\ Losses \end{pmatrix} + \begin{pmatrix} Iron \\ Losses \end{pmatrix} + \begin{pmatrix} Additional \\ Load \\ Losses \end{pmatrix} \tag{8}$$

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

a) Joule losses: part of electrical energy is converted into heat through the electric resistances found by the electric current in stator and rotor.

b) 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).

c) 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.

d) 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.

Motor losses distribution depends on the motor size and output power. Table 4 shows the typical distribution of motor losses in 4-pole AC induction motors and Table 5 presents the typical distribution of motor losses according to output power according to author Litman et al. [30].

Table 4 - Typical losses in an AC 4-pole induction motor [29]

	Typical losses in 4-pole motors	**Factors affecting these losses**
Stator losses	30 – 50%	Stator conductor size and material
Rotor losses	20 – 25%	Rotor conductor size and material
Core losses	20 – 25%	Type and quantity of magnetic material
Additional load losses	5 – 15%	Primarily manufacturing and design methods
Friction and windage	5 – 10%	Selection / design of fan and bearings

Table 5 - Typical distribution of motor losses (1800 rpm open drip proof enclosure) [30]

	25 HP	**50 HP**	**100 HP**
Stator losses	42%	38%	28%
Rotor losses	21%	22%	18%
Core losses	15%	20%	13%
Additional load losses	15%	12%	27%
Friction and windage losses	7%	8%	14%

Mechanical power is the force required to rotate the shaft, named torque, as defined by Equation 9.

$$P_{mec} = T_{mec}.\omega_R \tag{9}$$

According to IS, the unit for speed is rad/s, but most of motor manufacturers use the rpm unit (rotations per minute), so it is in this dissertation.

$$\omega_R = n_R.\frac{2\pi}{60} \tag{10}$$

$$P_{mec} = \frac{T_{mec}.n_R}{9550} \tag{11}$$

Electric motors are classified by their output mechanical power, it is an electrical language to say that certain motor is capable to deliver certain torque in its shaft at determined speed.

Therefore, for electric motors, the efficiency shall be computed as the output mechanical power divided by its input electric active power. The reactive power is not accounted as a loss.

$$\eta_M = \frac{P_{mec}}{S_{in,M}.\cos\varphi_M} \rightarrow \eta_M = \frac{P_{mec}}{\sqrt{3}.U_{in,M}.I_{in,M}.\cos\varphi_M} = \frac{P_{mec}}{P_{in,M}} \tag{12}$$

Direct measurement of output and input power are not always possible on test facilities, it usually dependent on the rated output power of the machine under test and the available equipment in the laboratory. Therefore IEC 60034-2-1&3 [8] [9] describes other available methods to determine efficiency of electric motors.

IEC 60034-2-1 [8] defines methods to calculate the total losses considering sinusoidal supply (direct on-line) and IEC 60034-2-3 [9] defines a methodology to compute the additional losses caused by the harmonics created by the CDM and consequently the efficiency of converted-fed induction motors.

According to IEC 60034-2-1 [8], for squirrel cage induction motors up to 2 MW the preferred testing method is the Method B – summation of losses with indirect measurement of additional load losses, determined from residual losses. This method requires in the test facility a dynamometer of at least 125% of full load output power.

The IEC 60034-2-3 [9] describes the additional tests to be performed on converter-fed induction motors to compute the harmonic losses. The additional tests shall be performed either with the converter to be used in final application (preferred) named string test, or if not possible, with a test converter available in the laboratory with full load current capability.

The following procedure describes all the steps required to test converter-fed induction motors up to 2 MW with the recommended methodology by IEC 60034-2-1&3 [8] [9].

Step 1 - Measurement of cold electric resistance

Parameters measured: θ_c and R_c.

Outputs:

θ_c – winding temperature at cold condition (at ambient temperature) (ºC);

R_c – winding resistance at cold condition (Ω).

Step 2 - Temperature rise test

Run the motor with rated input and output parameters until it reaches thermal equilibrium ($\Delta\theta_w$ > 1 K during at least 30 minutes).

Parameters measured: θ_w and R_w.

Related Equations:

$$k_\theta = \frac{235 + \theta_w + 25 - \theta_c}{235 + \theta_w} \tag{13}$$

Outputs:

θ_w – winding temperature at warm condition (ºC);

R_w – winding resistance at warm condition (Ω);

k_θ – temperature correction factor for 25ºC (-).

Step 3 - Rated load test

In thermal equilibrium and rated input and output parameters, measure input and output parameters.

Parameters measured:

$P_{in,M}$ – motor input active power (W);

$I_{in,M}$ – motor input rated current (A);

$U_{in,M}$ – motor input rated voltage (V);

T_{mec} – motor output rated mechanical torque (N.m);

$f_{in,M}$ – motor input rated frequency (Hz);

n_R – rotor rated rotational speed (rpm).

Related Equations:

$$P_{LS} = 1.5. R_w. I_{in,M}^2 \tag{14}$$

$$P_{LS\theta} = 1.5. R_w. I_{in,M}^2. k_\theta \tag{15}$$

$$n_S = \frac{120. f_{in,M}}{Poles} \tag{16}$$

$$s = \frac{n_S - n_R}{n_S} \tag{17}$$

$$P_{mec} = \frac{T_{mec}. n_R}{9550} \tag{18}$$

Note: Measured electric resistance R_c and R_w are the line-to-line measured resistance of the stator terminals, taken as the arithmetic average of the three terminals.

Stator losses are the same for either Y or Δ connected terminals, as followed demonstration.

For Y connected terminals:

$$R_{Phase(Y)} = \frac{R_{Line}}{2}$$

$$P_{LS} = 3.R_{Phase}.I_{in,M,Phase}^2 = 3.\frac{R_{Line}}{2}.I_{in,M,Line}^2 = 1.5.R_{Line}.I_{in,M,Line}^2 \tag{19}$$

For Δ connected terminals:

$$R_{Phase(\Delta)} = \frac{3R_{Line}}{2} = 1.5.R_{Line}$$

$$P_{LS} = 3.R_{Phase}.I_{in,M,Phase}^2 = 3.\frac{3R_{Line}}{2}.\left(\frac{I_{in,M,Line}}{\sqrt{3}}\right)^2 = 1.5.R_{Line}.I_{in,M,Line}^2 \tag{20}$$

Outputs:

P_{LS} – stator winding losses (W);

$P_{LS\theta}$ – stator winding losses temperature corrected (W);

n_S – rotor synchronous speed (rpm);

s – motor rated slip (pu);

P_{mec} – motor output rated mechanical power (W).

Step 4 - Load curve test

In thermal equilibrium, at rated voltage and frequency, variate input current to reach the six different torque outputs: 125%, 115%, 100% (rated), 75%, 50% and 25% (all at rated speed).

Measure input and output parameters for each of the six load conditions. Parameters and Equations are the same of step 3 but at part load condition.

Step 5 - No-load test

In thermal equilibrium, at rated frequency and no load, variate the input voltage on following recommended values: 110%, 100% (rated), 95%, 90% (for core loss determination) and 60%, 50%, 40%, 30% (for friction and windage loss determination).

Measure input parameters and calculate the constant losses for each no-load input voltage. These losses are constant for the six load conditions, including the rated.

Parameters measured:

P_0 – motor input no-load power (W);

I_0 – motor input no-load current (A);

U_0 – motor input no-load voltage (V).

Related Equations:

$$P_{Lcte} = P_0 - 1.5. R_w. I_0^2 \tag{21}$$

Output:

P_{Lcte} – constant losses (W).

Step 6 - Losses and efficiency calculation

Plot P_{Lcte} against U_0^2 considering the measurements done for 60%, 50%, 40% and 30% U_0. Extrapolate a straight line to U_0^2 = 0. The intercepted value of P_{Lcte} with the vertical axis is the friction and windage loss at no-load condition (when $n_S \cong n_R$).

$$U_0^2 = 0 \rightarrow P_{Lcte} = P_{Lfw0} \tag{22}$$

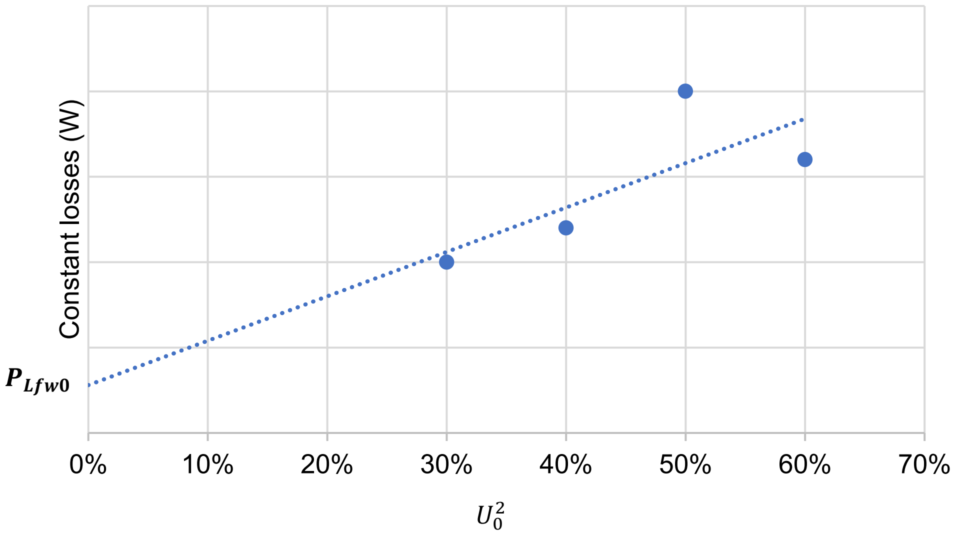


Figure 16 - Method to find the friction and windage loss at no load

Calculate the friction and windage loss at rated speed according Equation 23.

$$P_{Lfw} = P_{Lfw0}. (1 - s)^{2.5} \tag{23}$$

The difference between the constant losses and the friction and windage losses are the core loss.

IEC 60034-2-1 [8] requires the plot the difference between P_{Lcte} and P_{Lfw} versus U_0 considering the measurements done for 110%, 100% (rated), 95% and 90% U_0 and defines an internal voltage by which it should be considered the core loss. The internal voltage would be calculated by taking the no-load voltage equal to rated voltage minus the voltage drop on the stator ohmic resistance at load (phasor correction). However, Fitzgerald [28] says that the voltage correction is dismissed for induction motors and the core loss shall be determined at rated voltage ($100\%U_0 = U_{in,M}$). Therefore, in this dissertation, the internal voltage is not defined, and the core loss is defined by Equation 24.

$$P_{LFe} = P_{Lcte}\left(100\%U_0 = U_{in,M}\right) - P_{Lfw} \tag{24}$$

Calculate the rotor and the residual losses for each load condition, including the rated. Note the P_{Lfw} and P_{LFe} are constant for each load condition and do not require temperature correction.

$$P_{LR} = (P_{in,M} - P_{LS} - P_{LFe}).s \tag{25}$$

$$P_{LR\theta} = (P_{in,M} - P_{LS\theta} - P_{LFe}).s.k_\theta \tag{26}$$

$$P_{LRes} = P_{in,M} - P_{mec} - P_{LS} - P_{LR} - P_{Lfw} - P_{LFe} \tag{27}$$

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 the six load conditions).

A is the line slope and B is the interception on vertical axis. 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}.

$$P_{LRes} = A.T_{mec}^2 + B \tag{28}$$

$$P_{LL} = A.T_{mec}^2 \tag{29}$$

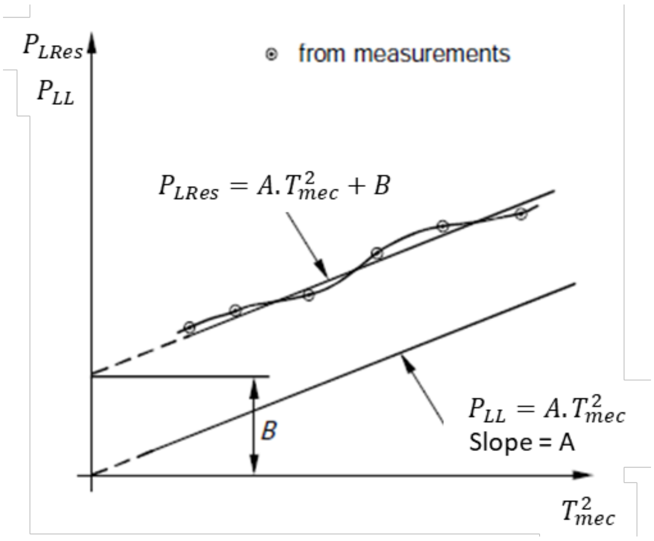


Figure 17 - Smoothing of residual loss to find the additional load loss [8]

The constant B should be considerably smaller (< 50%) than P_{LL} at rated torque as well as the correlation coefficient γ should be higher than 0.95. If any of these conditions are false, the measurements may be erroneous and should be repeated.

$$\gamma = \frac{i.\sum(P_{LRes}.T_{mec}^2) - (\sum P_{LRes}).(\sum T_{mec}^2)}{\sqrt{(i.\sum(T_{mec}^2)^2 - (\sum T_{mec}^2)^2).(i.\sum(P_{LRes})^2 - (\sum(P_{LRes})^2)^2)}} \tag{30}$$

Calculate the total losses and the efficiency considering the tests at sinusoidal supply (direct on-line).

$$P_{L,M@DOL} = P_{LS\theta} + P_{LR\theta} + P_{Lfw} + P_{LFe} + P_{LL} \tag{31}$$

$$\eta_{M@DOL} = \frac{P_{mec}}{P_{mec} + P_{L,M@DOL}} \tag{32}$$

Output:

P_{Lfw0} – friction and windage losses at no load (W);

P_{Lfw} – friction and windage losses at rated speed (W);

P_{LFe} – core losses (W);

P_{LR} – rotor winding loss (W);

$P_{LR\theta}$ – rotor winding loss temperature corrected (W);

P_{LRes} – residual losses (W);

P_{LL} – additional load losses (W);

$P_{L,M@DOL}$ – motor total losses at DOL supply (W);

$\eta_{M@DOL}$ – motor efficiency at DOL supply (%).

Step 7 - Additional harmonic losses for converter fed motors

IEC 60034-2-3 [9] requires repeating the previous steps but having the motor fed by converter supply. The difference between total losses at DOL condition and CDM condition would be the harmonic losses produced in the motor due to the non-sinusoidal voltage and current waveforms generated by the converter.

Unless if the final use CDM and motor should be tested together in a string test, it is not common for motors manufacturers to test the motors with a converter supply as motor datasheets are standardized with sinusoidal supply data.

Therefore, the standard IEC 60034-30-2 [19] determines a maximum allowed additional harmonic loss P_{LH}, which is based on several measurements according to IEC 60034-2-3 [9] and depend on converter switching frequency.

$$P_{LH} = r_H . P_{L,M@DOL} \tag{33}$$

Where:

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 4 kHz and recommended for motors with P_{mec} ≥ 90 kW.

The efficiency for CDM fed motors is determined by Equation 34.

$$\eta_{M@CDM} = \frac{P_{mec}}{P_{mec} + P_{L,M@DOL} + P_{LH}} \tag{34}$$

Output:

P_{LH} – additional harmonic losses (W);

r_H – additional harmonic loss factor (-);

$P_{L,M@CDM}$ – motor total losses at CDM supply (W);

$\eta_{M@CDM}$ – motor efficiency at CDM supply (%).

The previous procedure well determines the motor efficiency at rated and part load conditions, however it considers only the rated speed as it is written with the objective to find efficiency of direct on-line motors.

IEC 61800-9-2 [7] brings a different approach to determine motor efficiency and losses at any operating point (OP) of torque and speed based only on measured segregated losses at rated condition.

The fundamental motor input frequency and motor output mechanical torque are used as relative values referred to their rated values. The relative rated output power is therefore given by Equation 37.

$$f = \frac{f_{in,M@OP}}{f_{in,M}} \tag{35}$$

$$T = \frac{T_{mec@OP}}{T_{mec}} \tag{36}$$

$$P = \frac{P_{mec@OP}}{P_{mec}} = T.f \tag{37}$$

The interpolation equations can be used to find losses in the full base frequency ($f = 0 \ldots 1$) and torque ($T = 0 \ldots 1$) 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. It results in a slight reduction of interpolation precision but acceptable in practical applications.

The following Equations 38 to 46 are described by IEC 61800-9-2 [7] Annex D to determine the relative losses at any operating point (f, T) considering the segregated losses defined in IEC 60034-2-1&3 [8] [9] are known at least for the rated condition.

Stator and rotor winding losses are independent of frequency and vary with the square of torque (since current basically varies with torque), considering the no-load current offset.

$$P_{LSR}(f,T) = P_{LSR}(f_{in,M}, T_{mec}).\left[\left(\frac{I_0}{I_{in,M}}\right)^2 + \left(1 - \left(\frac{I_0}{I_{in,M}}\right)^2\right).T^2\right] \tag{38}$$

Core loss can be separated in two parts: hysteresis losses $K_{Fe}.P_{LFe}$ that are proportional to the frequency and Foucault losses $(1 - K_{Fe}).P_{LFe}$ that depends on the square of frequency.

For induction machines, there is no dependence of core losses on torque within the base speed range ($f = 0 \ldots 1$), once magnetic flux is constant and independent of load current.

$$P_{LFe}(f,T) = P_{LFe}(f_{in,M}, T_{mec}).[K_{Fe}.f + (1 - K_{Fe}).f^2] \tag{39}$$

Friction and windage losses are split in two parts: friction loss $K_{fw}.P_{Lfw}$ proportional to the frequency and windage loss $(1 - K_{fw}).P_{Lfw}$ proportional to the third power of speed.

According to IEC 61800-9-2 [7], several tests have proved that the third power of frequency (speed) term brings slight measurement errors, therefore this term shall be disregard on the interpolation equation. The standard is not clear if the term should be replaced by a square power or simply disregard. In this dissertation the term in the third power of frequency is replaced by the square power of frequency.

$$P_{Lfw}(f,T) = P_{Lfw}(f_{in,M}, T_{mec}).\left[K_{fw}.f + (1 - K_{fw}).f^2\right] \tag{40}$$

The additional losses can also be divided in two terms: $K_{LL}.P_{LL}$ that depends on frequency and the square of torque; and $(1 - K_{LL}).P_{LL}$ that depends on the square of frequency and torque.

$$P_{LL}(f,T) = P_{LL}(f_{in,M}, T_{mec}).\left[K_{LL}.f.T^2 + (1 - K_{LL}).f^2.T^2\right] \tag{41}$$

The standard states that when the exact distribution of each loss is not known, the constants K_{Fe}, $K_{fw,}$ K_{LL} can assume the value 0.5 (50%).

The additional harmonic loss is considered constant over the whole frequency and torque range if the converter switching frequency remains unchanged.

$$P_{LH}(f,T) = P_{LH}(f_{in,M}, T_{mec}) \tag{42}$$

The total losses can be then calculated for any operating point by summing up all the segregated losses previously determined.

$$P_{L,M@CDM}(f,T) = P_{LSR}(f,T) + P_{LFe}(f,T) + P_{Lfw}(f,T) + P_{LL}(f,T) + P_{LH}(f,T) \tag{43}$$

The relative total loss is determined as a percentage of motor rated output power.

$$P_{L,M@CDM,Relative}(f,T) = \frac{P_{L,M@CDM}(f,T)}{P_{mec}} \tag{44}$$

The motor efficiency for any operating point shall be determined according to Equation 45.

$$\eta_{M@CDM}(f,T) = \frac{f.T}{f.T + P_{L,M@CDM,Relative}} \tag{45}$$

If the efficiency is known, the relative loss can be determined by Equation 46.

$$P_{L,M@CDM,Relative} = f.T.\left(\frac{1}{\eta_{M@CDM}(f,T)} - 1\right) \tag{46}$$

4.1.1.Electric motor efficiency class determination

Efficiency classes for three phase AC squirrel cage electric motors are well defined according to IEC 60034-30-1 [18] as IE1, IE2, IE3 or IE4. This standard provides efficiency references for 50 and 60 Hz motors, independent of voltage.

Table 6 - IE classes for electric motors [18]

No designation	Below standard efficiency
IE1	Standard efficiency
IE2	High efficiency
IE3	Premium efficiency
IE4	Super premium efficiency

In Europe, the current Commission Regulation (EC) 640/2009 [4], valid until 30 June 2021, regulates safe area motors, 2-6 poles and output power between the range 0.75 kW ≤ P_{mec} ≤ 375 kW (Figure 18). The minimum efficiency class shall be IE3 for direct on-line motors and IE2 for CDM fed motors. Special applications and hazardous area motors are not regulated.

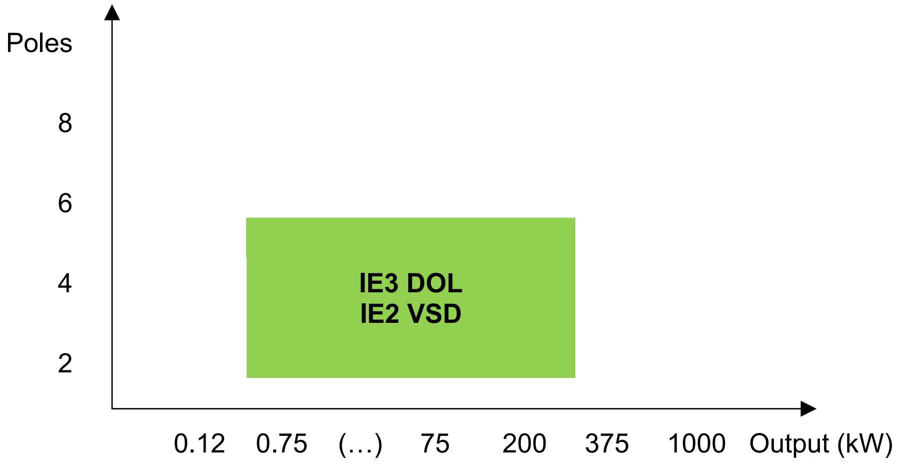


Figure 18 - Electric motors minimum efficiency regulation valid until 30 June 2021 [4]

The Commission Regulation 2019/1781 [5] replaces the (EC) 640/2009 [4]. The implantation shall occur in two steps.

Step 1 valid from 1 July 2021, divided into two groups (Figure 19):

a. Safe and hazardous area motors (except Ex eb), 2-8 poles, DOL or VSD, with or without brake, TEAO inclusive, and with output power 0.75 kW ≤ P_{mec} ≤ 1000 kW, shall comply with IE3 class.

b. Safe and hazardous area motors (except Ex eb), 2-8 poles, DOL or VSD, with or without brake, TEAO inclusive, and with output power 0.12 kW ≤ P_{mec} < 0.75 kW, shall comply with IE2 class.

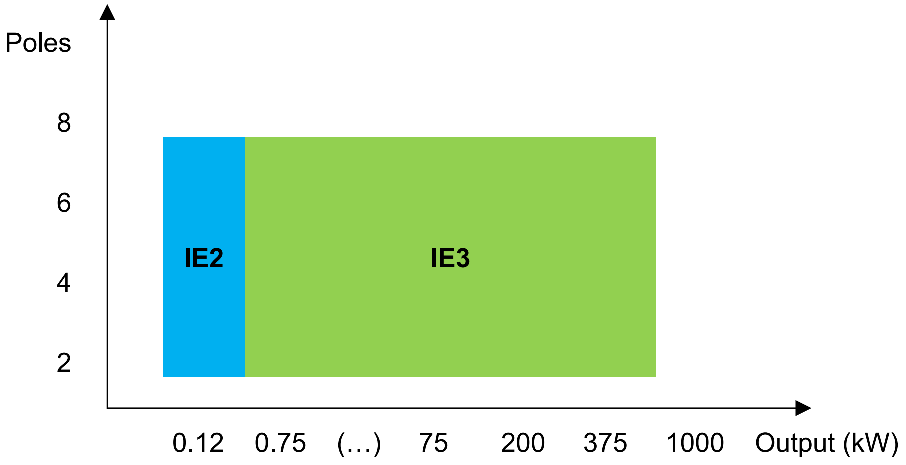


Figure 19 - Electric motors minimum efficiency regulation valid from 1 July 2021 [5]

Step 2 valid from 1 July 2023, divided into four groups:

a. Safe area, 2-6 poles, DOL or VSD, and with output power 75 kW ≤ P_{mec} ≤ 200 kW, shall comply with IE4 class. Special applications and hazardous area not inclusive (Figure 20).

b. Except for paragraph "*a*" abovementioned, safe and hazardous area motors (except Ex eb), 2-8 poles, DOL or VSD, with or without brake, TEAO inclusive, and with output power 0.75 kW ≤ P_{mec} ≤ 1000 kW, shall comply with IE3 class (Figure 20).

c. Except for paragraph "*a*" abovementioned, safe and hazardous area motors (except Ex eb), 2-8 poles, DOL or VSD, with or without brake, TEAO inclusive, and with output power 0.12 kW ≤ P_{mec} < 0.75 kW, shall comply with IE2 class (Figure 20).

d. Hazardous area Ex eb, 2-8 poles, DOL or VSD, and with output power 0.12 kW ≤ P_{mec} ≤ 1000 kW, shall comply with IE2 class (Figure 21).

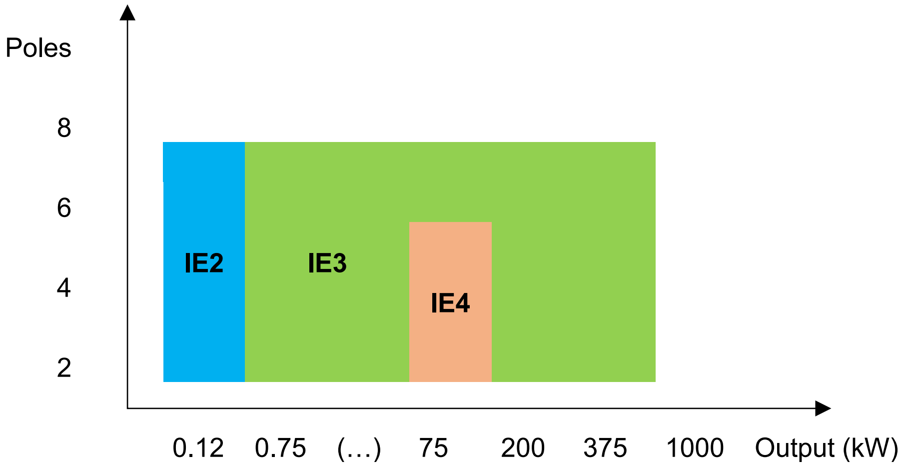


Figure 20 - Electric motors minimum efficiency regulation valid from 1 July 2023 [5]

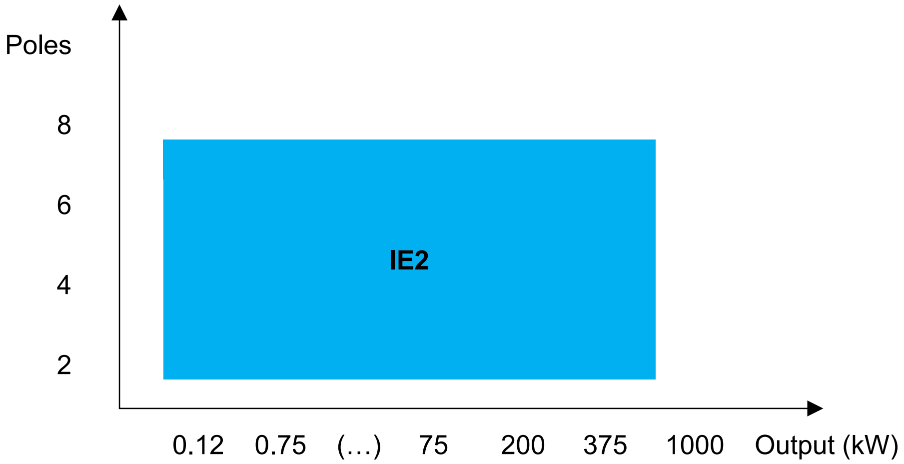


Figure 21 - Ex eb electric motors minimum efficiency regulation valid from 1 July 2023 [5]

As the current regulation defines IE2 as the minimum efficiency class for motors operating with CDM, IEC 61800-9-2 [7] defines the Reference Motor (RM) with relative losses calculated according to the methodology described in this chapter and based on IE2 4-pole 50 Hz motors. This standard provides a table with reference motor's relative losses for the 8 pre-defined operating points (f, T), as shown in Figure 22.

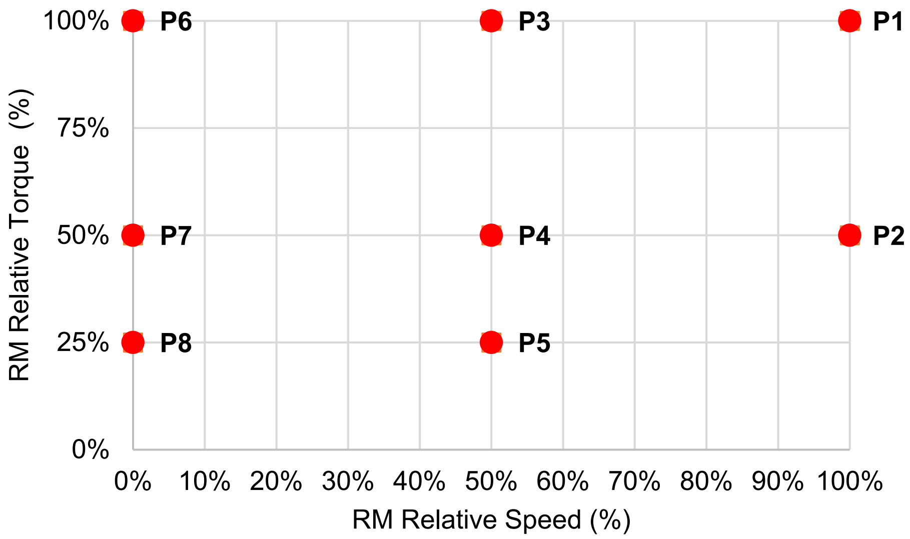


Figure 22 - Operating points for reference motor's relative losses determination [7]

4.2. Complete Drive Module (CDM)

Complete Drive Module (CDM) is the electronic power converter equipment connected between the grid and the motor. It absorbs and deliver electrical apparent power. The CDM output apparent power is the motor input apparent power which is considered the CDM rated power.

$$S_{out,CDM} = S_{in,M} \tag{47}$$

CDMs are usually rated according to their output current rather than their apparent output power. The relation between rated output apparent power and current is given by Equation 48.

$$S_{out,CDM} = \sqrt{3}.U_{out,CDM}.I_{out,CDM} \tag{48}$$

The standard IEC 61800-2 [7] describes the CDM as a drive module consisting of, but not limited to, the Basic Drive Module (BDM) and extensions such as protection devices, filters and auxiliaries, but excluding the motor and the sensors which are mechanically coupled to the motor shaft.

A BDM is a power electronic device composed basically by a rectifier bridge that converts alternating voltage (AC) of the grid at 50 Hz or 60 Hz to direct voltage (DC) on DC link capacitors; and an inverter bridge that converts the DC voltage of the DC link to AC voltage at the desired frequency to feed the motor. In this dissertation the BDM is also referred as variable speed drive (VSD).

There are two main goals of feeding the motor with a CDM device: to variate and control the motor speed and to enable the motor acceleration smoothly when it is coupled to high inertia loads.

The CDM controls the motor supply by variating the output voltage and frequency by the same proportion in order to keep the magnetic flux constant inside the motor, that allows the motor to deliver the rated output torque within the whole speed range keeping its absorbed current at rated level. This is valid up to rated voltage (operation zone), beyond this point the voltage remain constant while the frequency increases, leading to the magnetic field weakening zone (where an extrapolation of the methodology is not allowed).

The rectifier diode bridge conducts the current from the grid to the DC link in a discontinuous way, therefore the CDM is considered a non-linear load to the grid. The non-linear current wave is a composition of a fundamental wave at grid rated frequency (50 Hz or 60 Hz) and other multiples of the fundamental wave at higher frequency, named harmonics. For three-phase CDMs the most significant harmonics are the 5th and 7th orders (250 Hz and 350 Hz if the fundamental is 50 Hz). The total harmonic distortion on current is given by Equation 49.

$$THDi = \frac{\sqrt{I_{h5}^2 + I_{h7}^2 + \cdots + I_{hn}^2}}{I_{1,in,CDM}} \tag{49}$$

Harmonic distortion increases the RMS value of the CDM absorbed current and the absorbed apparent power related to this incremental current is not converted into useful mechanical power on the motor output. That means harmonics are considered losses for the system, but it is not accounted on the total CDM losses as it is characterized by the CDM power factor λ.

$$I_{in,CDM} = I_{1,in,CDM} \cdot \sqrt{1 + THDi^2} \tag{50}$$

$$\lambda = \frac{P_{in,CDM}}{S_{in,CDM}} = \frac{\sqrt{3}.\,U_{1,in,CDM} \cdot I_{1,in,CDM} \cdot \cos\varphi_{in,CDM}}{\sqrt{3}.\,U_{1,in,CDM} \cdot I_{1,in,CDM} \cdot \sqrt{1 + THDi^2}} = \frac{\cos\varphi_{in,CDM}}{\sqrt{1 + THDi^2}} \tag{51}$$

Where $\cos\varphi_{in,CDM}$ is the CDM input displacement factor related to the angle between the fundamental CDM input voltage and the fundamental CDM input current.

An important remark is that the CDM input displacement factor $(\cos\varphi_{in,CDM})$ is different than the CDM output displacement factor $(\cos\varphi_{out,CDM})$ and also different than the CDM power factor (λ).

$$\cos\varphi_{in,CDM} > \cos\varphi_{out,CDM} \tag{52}$$

$$\lambda \leq \cos\varphi_{in,CDM} \tag{53}$$

Motor power factor is the CDM output displacement factor $(\cos\varphi_M = \cos\varphi_{out,CDM})$. The CDM input displacement factor $(\cos\varphi_{in,CDM})$ is higher than motor power factor $(\cos\varphi_{out,CDM})$ because the CDM uses its internal capacitor bus to supply any reactive current the motor absorbs (inductive), thereby neutralizing the reactive absorbed current from the grid and increasing CDM input displacement factor.

On the other hand, the CDM power factor (λ) is lower than the CDM input displacement factor $(\cos\varphi_{in,CDM})$ due to the harmonic distortion on absorbed current (Equation 51), except for Active Infeed Converters which are able to absorbs nearly sinusoidal currents.

Harmonic distortion on current wave may also cause harmonic distortion on voltage wave, a non-sinusoidal voltage supply is the major concern of the power supply company as it causes disturbances on other installations connected to the same power circuit. The value of the $THDv$ depends on the voltage and short-circuit levels at the Point of Common Coupling (PCC) and shall be analyzed as a whole, considering all the connected loads to this PCC, not the distortion of one individual CDM.

Nevertheless, there are a variety of filtering configurations available to correct harmonic distortions. Some filters are installed inside the CDM and others are set to correct the harmonic distortion of the summation of non-linear loads connected to the PCC. For the CDM total loss determination purpose, only the filters installed inside the CDM shall be considered.

Figure 23 shows an example of PDS with the main components that may be part of the CDM. All the block components are suitable to losses as it is described within this chapter.

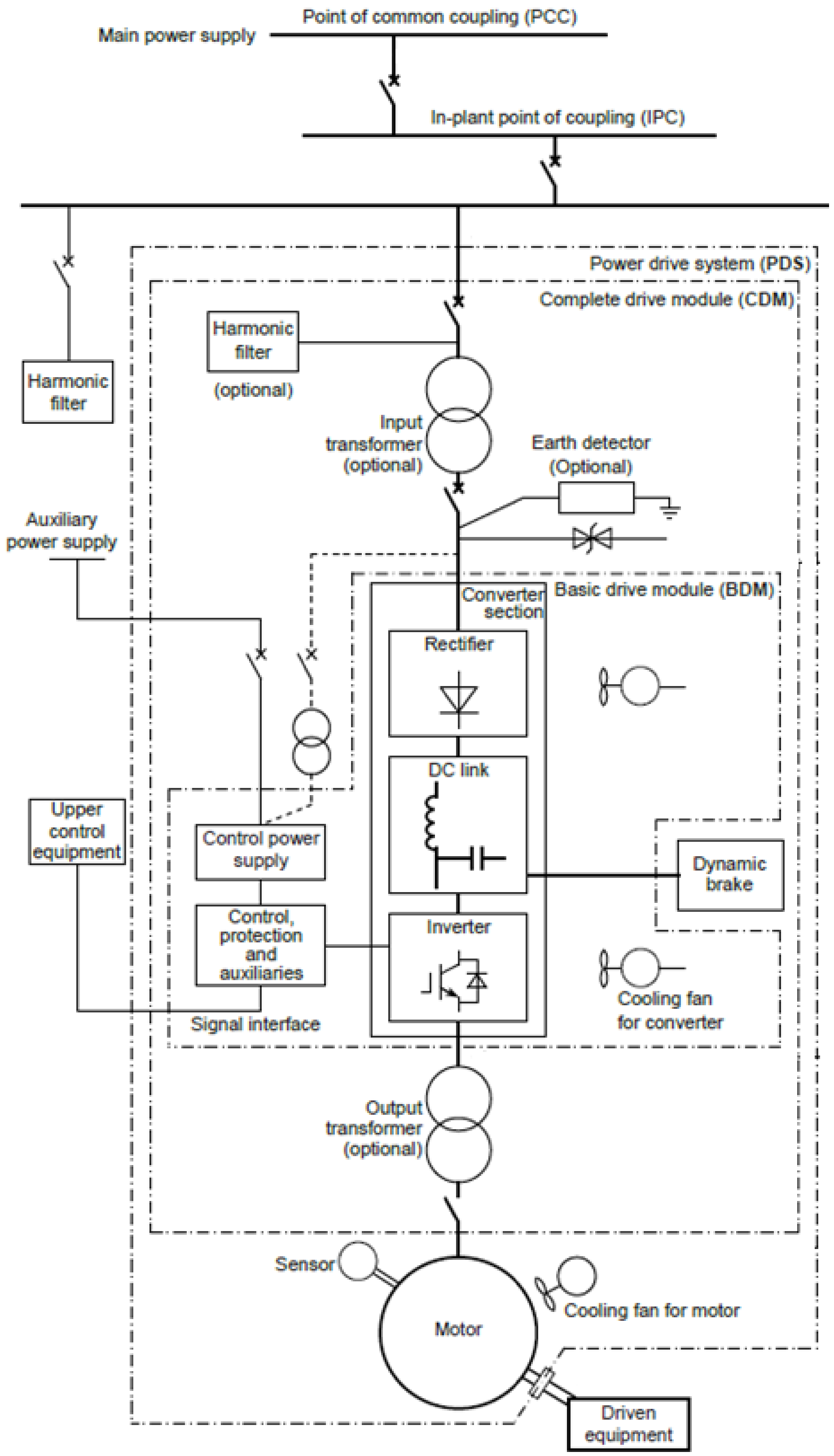


Figure 23 - Example of a PDS [31]

It is the goal of IEC 61800-9-2 [7] 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 speed must be correlated to CDM output frequency. As previously mentioned, the motor relative output speed can be considered identical to the grid supplied relative frequency, disregarding the slip. It is not different if the grid supply is replaced by CDM supply, therefore 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.

Due to its scalar operation principle, CDM relative output voltage shall be considered the same as CDM relative output frequency 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. CDM losses at 90% and at 100% output voltage are approximately the same, therefore they are considered the same in this method.

Table 7 - 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 [7] describes the equations to determine the CDM relative losses as a summation of losses in each part of the CDM, simplified in Figure 24.

Some parameters are provided as typical values for a Reference CDM (RCDM) in the realm of the IEC 61800-9-2 [7] approach. Manufacturers are free to consider the real values of CDM parameters.

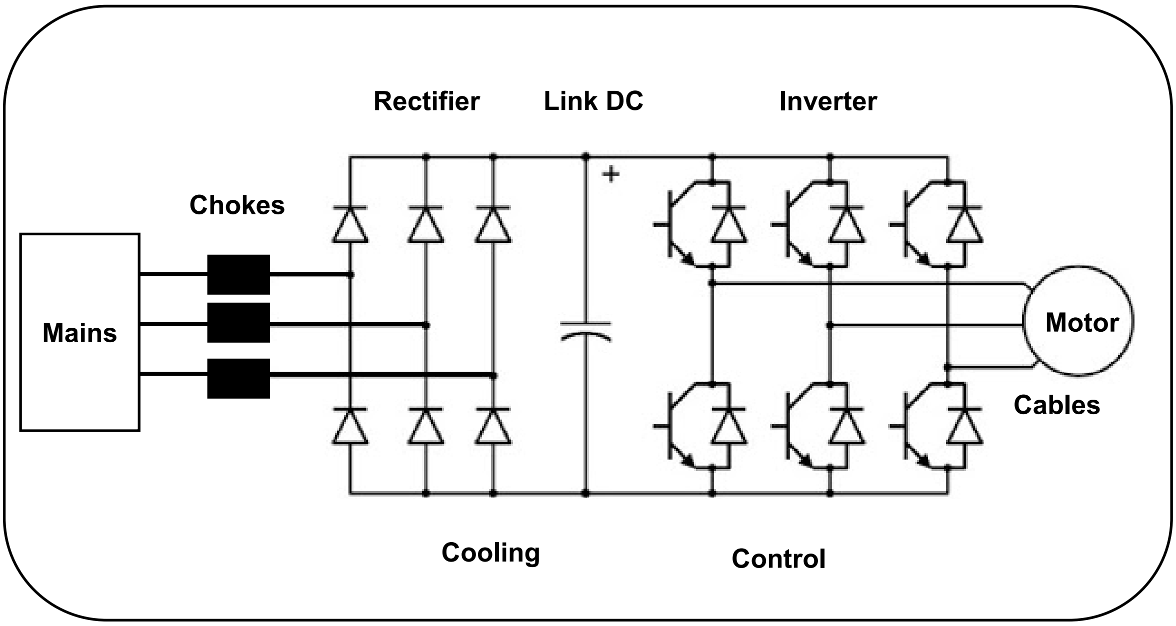


Figure 24 - Parts of reference CDM [7]

4.2.1.Output inverter losses

It is the major part of CDM losses.

$$\begin{aligned}P_{L,on,T} &= \sqrt{2}.I_{out,CDM@OP}.U_{T,th}.\left(\left(\frac{1}{2\pi}\right)+\frac{1.22.m.\cos\varphi_{out,CDM@OP}}{8}\right)\\ &\quad+\frac{U_{T,on}-U_{T,th}}{I_{out,CDM}}.2.I^{2}_{out,CDM@OP}.\left(\frac{1}{8}+\frac{1.22.m.\cos\varphi_{out,CDM@OP}}{3\pi}\right)\end{aligned} \tag{54}$$

$$\begin{aligned}P_{L,on,D} &= \sqrt{2}.I_{out,CDM@OP}.U_{D,th}.\left(\left(\frac{1}{2\pi}\right)-\frac{1.22.m.\cos\varphi_{out,CDM@OP}}{8}\right)\\ &\quad+\frac{U_{D,on}-U_{D,th}}{I_{out,CDM}}.2.I^{2}_{out,CDM@OP}.\left(\frac{1}{8}-\frac{1.22.m.\cos\varphi_{out,CDM@OP}}{3\pi}\right)\end{aligned} \tag{55}$$

$$P_{L,sw,T} = \frac{E_T}{\pi}.U_{DC}.\sqrt{2}.\left(I_{out,CDM@OP}+I_{motor_{cable}}\right).f_{sw} \tag{56}$$

$$P_{L,sw,D} = \frac{E_D}{\pi}.U_{DC}.\sqrt{2}.\left(I_{out,CDM@OP}+I_{motor\_cable}\right).f_{sw} \tag{57}$$

$$P_{L,inverter} = 6.\left(P_{L,on,T}+P_{L,on,D}+P_{L,sw,T}+P_{L,sw,D}\right) \tag{58}$$

The variables to compute inverter losses are $I_{out,CDM@OP}$, $\cos\varphi_{out,CDM@OP}$ and m.

The typical reference parameters provided by the standard are:

$m = f$ – modulation index, identical to the relative CDM output frequency up to rated frequency (-);

$U_{T,th} = 1.0$ – transistor typical IGBT threshold voltage (V);

$U_{T,on} = 2.3$ – transistor typical IGBT on state voltage at CDM output rated current (V);

$U_{D,th} = 1.1$ – diode typical threshold voltage (V);

$U_{D,on} = 2.4$ – diode typical on state voltage at CDM output rated current (V);

$E_T = 7.5.10^{-7}$ – transistor typical IGBT switching ON and OFF loss energy (J/V.A);

$E_D = 2.5.10^{-7}$ – diode typical switching ON and OFF loss energy (J/V.A);

$U_{DC} = 540$ – CDM typical DC link voltage (V);

I_{motor_cable} – typical additional current due to ohmic losses on cable between motor and CDM (A):

$$I_{motor\_cable} = \begin{cases} 4, & I_{out,CDM} \leq 4; \\ I_{out,CDM}, & 4 < I_{out,CDM} < 10; \\ 10, & I_{out,CDM} \geq 10; \end{cases}$$

f_{sw} – switching frequency (Hz):

$$f_{sw} = \begin{cases} 4000, & P_{mec} \leq 90kW; \\ 2000, & P_{mec} > 90kW. \end{cases}$$

4.2.2. Diode rectifier losses

$$P_{L,rectifier} = 6.\left(\frac{\sqrt{2}}{\pi}.m.\cos\varphi_{out,CDM@OP}.I_{out,CDM\,@OP}.U_{D,th,rec} + \frac{U_{D,on,rec} - U_{D,th,rec}}{\cos\varphi_{\,out,CDM}.I_{out,CDM}}.\frac{1}{2}.\left(\frac{m.\cos\varphi_{out,CDM\,@OP}.I_{out,CDM@OP}}{\lambda}\right)^2\right) \quad (59)$$

The variables to compute rectifier losses are $I_{out,CDM@OP}$, $\cos\varphi_{out,CDM@OP}$ and m.

The typical reference parameters provided by the standard are:

$U_{D,th,rec} = 0.9$ – rectifier diode typical threshold voltage (V);

$U_{D,on,rec} = 2.2$ – rectifier diode typical ON state voltage at CDM input rated current (V).

The CDM power factor λ depends on the input converter topology, typical values are provided in Table 8.

Table 8 - CDM typical power factor [7]

Input converter topology	Value of λ
Large DC link capacitor with 0.5% input choke	0.6
Large DC link capacitor with 4% input choke	0.7
Small DC link capacitor according to IEC TS 62578	0.9
Active infeed converter with high switching frequency	1.0

If the input converter section consists of an Active Infeed Converter (AIF), its losses shall be calculated in an identical way as the output inverter section. In this case, the output parameters (current and displacement factor) of the active infeed part is the grid input parameters of the CDM. The converter is able to absorb nearly sinusoidal current due to the high switching frequency of the IGBTs and the controllable phase angle between input current and voltage leads to a nearly unitary displacement factor (what is equal to the power factor if current harmonic distortion is null).

4.2.3.Line chokes losses

Low frequency line harmonic filters (chokes) are frequently used to reduce harmonics on the grid side.

Although a low harmonic distortion is interesting for losses reduction, the inductive component of the filters themselves also produces losses.

DC chokes may be used in the DC link replacing AC line input chokes. Losses in DC and AC chokes are in the same order of magnitude.

$$P_{L,choke} = k1_{choke}.k2_{choke}.\sqrt{3}.\frac{\left(\frac{m.\cos\varphi_{out,CDM@OP}.I_{out,CDM@OP}}{\lambda}\right)^2}{\cos\varphi_{out,CDM}.I_{out,CDM}}.\frac{U_{in,CDM}}{\sqrt{3}} \quad (60)$$

The variables to compute chokes losses are $I_{out,CDM@OP}$ and $\cos\varphi_{out,CDM@OP}$.

The typical reference parameters provided by the standard are:

$k1_{choke} = 0.02$ – typical choke impedance, relative to the CDM rated impedance (-);

$k2_{choke} = 0.25$ – typical relative voltage drop on the resistive part of the choke (-).

4.2.4.DC link losses

$$P_{L,DC\_link} = k1_{DC\_link}.I_{out,CDM}.U_{DC}^2 + k2_{DC\_link}.\frac{\left(\frac{\sqrt{3}}{1.35}.\frac{m.\cos\varphi_{out,CDM@OP}.I_{out,CDM@OP}}{1+50.k1_{choke}}\right)^2}{I_{out,CDM}} \quad (61)$$

The variables to compute DC link losses are $I_{out,CDM@OP}$ and $\cos\varphi_{out,CDM@OP}$.

The typical reference parameters provided by the standard are:

$k1_{DC\_link} = 8.10^{-7}$ – typical load independent DC link loss parameter $(\Omega\text{A})^{-1}$;

$k2_{DC\_link} = 2$ – typical load dependent DC link loss parameter (ΩA).

4.2.5.Cable losses

The resistive behavior of the cable between CDM and motor causes losses proportional to the CDM output current.

$$P_{L,rails} = \frac{U_{rails}}{I_{out,CDM}}.I_{out,CDM@OP}^2 \quad (62)$$

The variable to compute DC link losses is $I_{out,CDM@OP}$ only.

The typical reference parameter provided by the standard is:

$U_{rails} = 0.7$ – typical voltage drop at CDM to motor cables due to CDM output rated current (V).

4.2.6.Control and standby losses

Control and standby losses usually do not depend significantly on the CDM rated power, to estimate the proper losses the evaluation must consider the automation system as a whole and the control functions of the PDS.

The typical reference control and standby losses provided by the standard is:

$P_{L,control} = 50$ – typical control and standby losses (W).

4.2.7.Cooling losses

Usually CDMs are installed inside an air-conditioned room that keep the inside temperature below a certain value (usually +40ºC). As a minimum, this cooling system shall carry all the CDM losses out of the room, for that reason the power consumption of this external cooling system shall be considered in the PDS losses computation itself.

$$P_{L,cooling} = k_{L,cooling} \cdot \left(P_{L,inverter} + P_{L,rectifier} + P_{L,choke} + P_{L,DC\_link} + P_{L,rails} + P_{L,control}\right) \tag{63}$$

The typical reference parameter provided by the standard is:

$k_{L,cooling} = 0.2$ – typical cooling losses parameter at CDM rated condition (-).

4.2.8.Overall CDM losses

The total losses can be then calculated for any operating point by summing up all the losses previously determined. And the relative losses are determined as a percentage of the output rated power.

$$\begin{aligned} P_{L,CDM}(f,T) = {} & P_{L,inverter}(f,T) + P_{L,rectifier}(f,T) + P_{L,choke}(f,T) + P_{L,DC\_link}(f,T) + P_{L,rails}(f,T) \\ & + P_{L,control}(f,T) + P_{L,cooling}(f,T) \end{aligned} \tag{64}$$

$$P_{L,CDM,Relative}(f,T) = \frac{P_{L,CDM}(f,T)}{S_{out,CDM}} \tag{65}$$

4.2.9. CDM efficiency class determination

According to IEC 61800-9-2 [7] it is now possible to classify the CDM in efficiency classes as it is well defined for electric motors by IEC 60034-30-1 [18].

IEC 61800-9-2 [7] provides a table with reference CDM's (RCDM) relative losses for all typical CDM power ratings and for the 8 pre-defined operating points (f,T) as shown in Figure 25 and based on the methodology above described in this chapter.

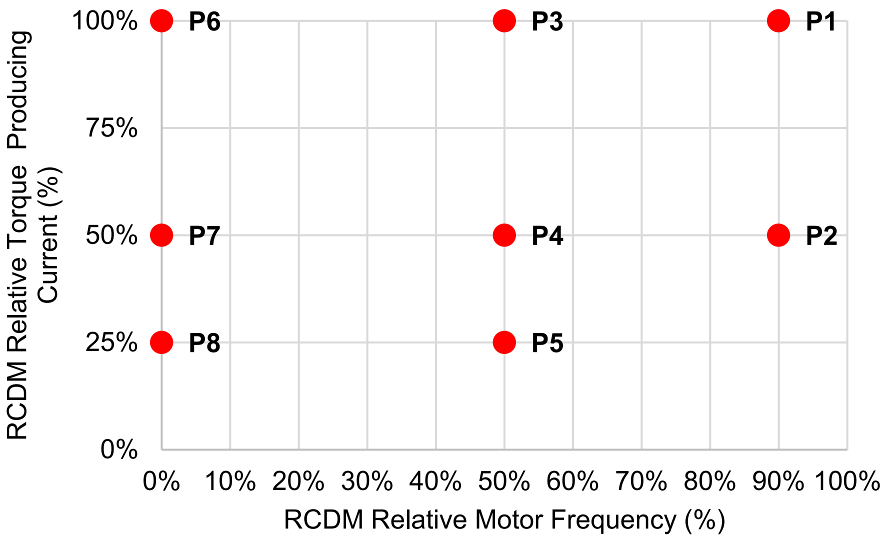


Figure 25 - Operating points for reference CDM's relative losses determination [7]

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 [5] 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."

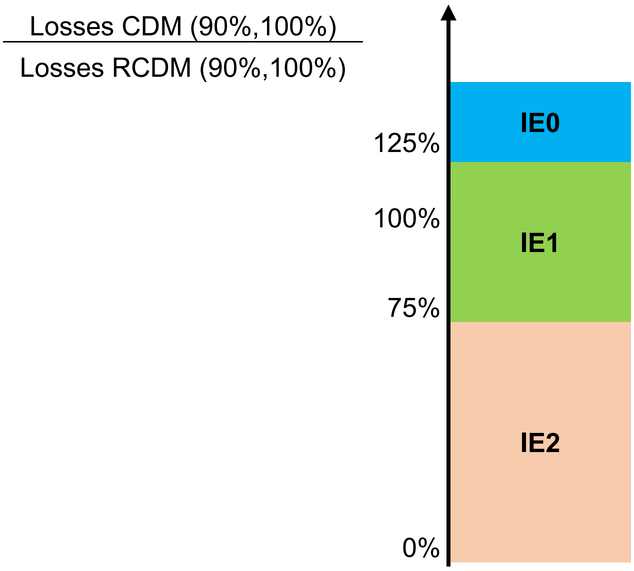


Figure 26 - IE classes of a CDM [7]

If the rated apparent power of a CDM is between two values of the RCDM table, the relative loss value of the RCDM with the next higher apparent power rating shall be used for IE class determination.

4.3. Power Drive System (PDS)

The PDS losses are the summation of CDM losses and motor losses at each pre-defined operating point (f, T). If any auxiliary is included, its losses shall be added.

$$P_{L,PDS}(f,T) = P_{L,CDM}(f,T) + P_{L,M@CDM}(f,T) \tag{66}$$

At any combination of frequency and torque, the PDS losses determination shall be done by Equation 66. However, PDS loss at rated condition (100% speed, 100% torque) is determined according to Equation 67 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}.

$$P_{L,PDS}(100\%, 100\%) = P_{L,CDM}(90\%, 100\%) + k_{VD} \,. P_{L,M@CDM}(100\%, 100\%) \tag{67}$$

The PDS loss calculation method assumes that CDM loss at 100% frequency and 90% voltage are the same as losses at 90% frequency and 90% voltage.

Therefore, 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).

4.3.1.PDS efficiency class determination

A table with relative losses of reference PDS (RPDS) is also provided by standard IEC 61800-9-2 [7] for all typical PDS power ratings (identical to motor power ratings from IEC 60034-30-1 [18]). The table is based on the application of Equations 66 and 67, summing up the relative losses of RCDM and RM.

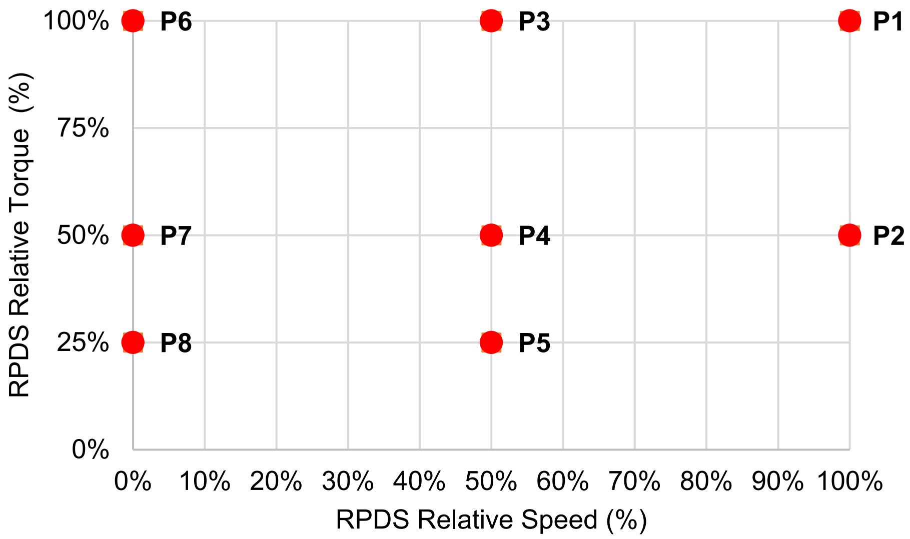


Figure 27 - Operating points for reference PDS's relative losses determination [7]

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.

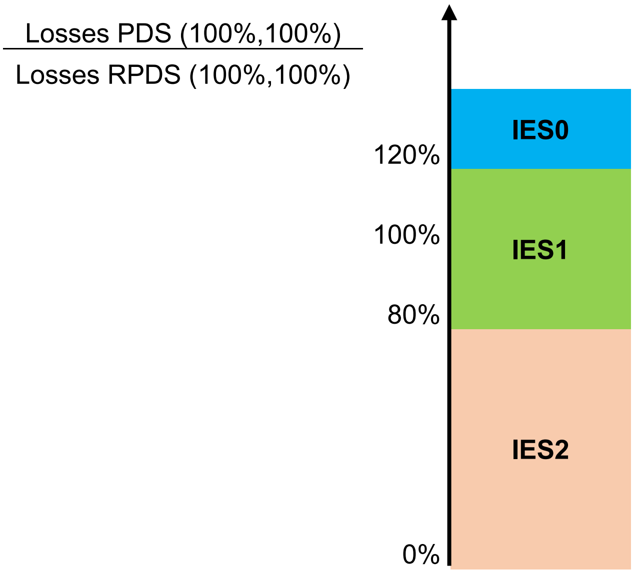


Figure 28 - IEC classes of a PDS [7]

If the rated power of a PDS is between two values of the RPDS table, the relative loss value of the RPDS with the next higher power rating shall be used for IES class determination.

4.4. Driven equipment

The driven equipment is composed of a mechanical transmission and the load machine. The mechanical transmission can be a flexible coupling, a gearbox, or pulley-belt device. This dissertation considers a gearbox equipment connected between the electric motor and the load machine.

The gearbox is a group of gears that convert lower mechanical torque at higher speed on motor shaft into higher mechanical torque at lower speed into load machine shaft. The efficiency is calculated as output mechanical power divided by input mechanical power and losses are basically tooth friction and lubrication churning losses.

The load machine can be of a variety types that requires a shaft torque to function. In this dissertation the load machine is an axial fan part of an induced draft cooling tower application.

The efficiency of a cooling tower depends, among other factors, on the efficiency of its axial fan. A cooling tower is a construction that cools down a fluid, which description is out of the scope of this dissertation. The efficiency of the axial fan is the goal of this sub-chapter.

Figure 29 shows the driven equipment arrangement considered in this dissertation (gearbox and axial fan) coupled to an electric motor.

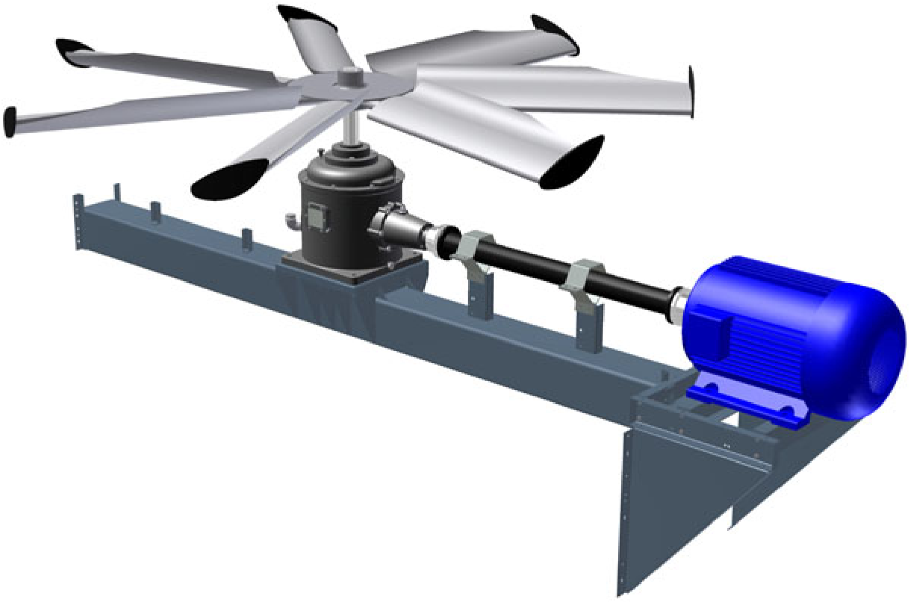


Figure 29 - Driven equipment arrangement (gearbox and axial fan) coupled to an electric motor [32]

Fan is a rotary bladed machine that receives mechanical energy and utilizes it by means of one or more impellers fitted with blades to maintain a continuous flow of air or other gas passing through it and whose work per unit mass does not normally exceed 25 kJ/kg. A fan as defined in Regulation 327/2011 [10] 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 [33]. Fan is a turbomachine that supplies energy to an incompressible gas, resulting in an increase of the fluid kinetic energy and enthalpy [34].

Figure 30 shows the adapted Extended Product including the detailed driven equipment.

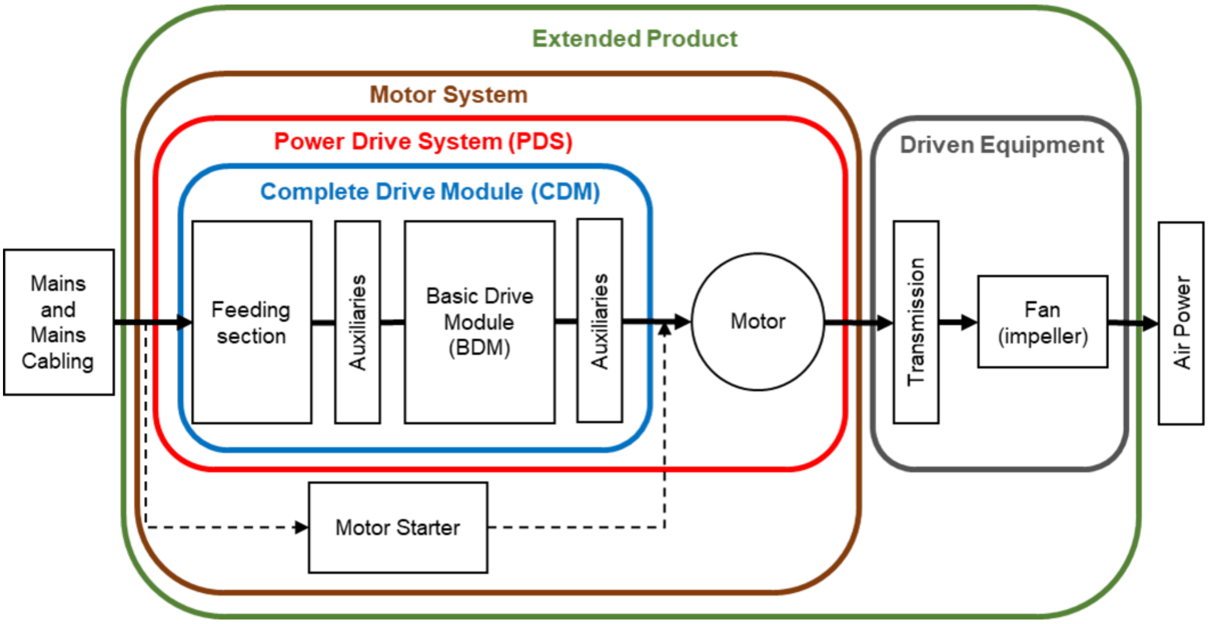


Figure 30 - Extended Product considering the driven equipment as a fan [33]

Fans are classified as axial, centrifugal, cross flow or mixed flow.

'Axial fan' means a fan that propels gas in the axial direction to the rotational axis of one or more impeller(s) with a swirling tangential motion created by the rotating impeller(s). The axial fan may or may not be equipped with a cylindrical housing, inlet or outlet guide vanes [10]. In this dissertation it is considered an axial fan with one impeller, without housing and without guide vanes.

The impeller is the part of the fan that is imparting energy into the gas flow.

Fans convert the mechanical power (shaft torque) supplied by an electric motor through the gearbox into gas power. Fan gas power is the product of gas volume flow rate q and pressure difference across the fan. The pressure is either the static pressure p_{sf} or the total pressure p_f, the latter is the sum of static and dynamic pressure as defined by Equation 68.

$$p_f = p_{sf} + \frac{\rho . V^2}{2} \tag{68}$$

According to Commission Regulation (EU) 327/2011 [10], the fan gas power is calculated according to the measurement category test method chosen by the fan supplier:

- Measurement category A: the fan is measured with free inlet and outlet conditions. The fan static gas power P_{us} shall be computed according to Equation 69.

$$P_{us} = q . p_{sf} . k_{ps} \tag{69}$$

- Measurement category B: the fan is measured with free inlet and with a duct fitted to its outlet. The fan gas power P_u shall be computed according to Equation 70.

$$P_u = q . p_f . k_p \tag{70}$$

- Measurement category C: the fan is measured with a duct fitted to its inlet and with free outlet conditions. The fan static gas power P_{us} shall be computed according to Equation 71.

$$P_{us} = q.p_{sf}.k_{ps} \tag{71}$$

- Measurement category D: the fan is measured with a duct fitted to its inlet and outlet. The fan gas power P_u shall be computed according to Equation 72.

$$P_u = q.p_f.k_p \tag{72}$$

The volume flow rate q can be calculated by the mass flow rate of gas moved by the fan $\dot{m}$ (kg/s) divided by the density of this gas at the fan inlet ρ (kg/m³).

$$q = \frac{\dot{m}}{\rho} \tag{73}$$

Compressibility factor is a dimensionless number that describes the amount of compressibility that the gas stream experiences during the test and is calculated as the ratio of the mechanical work done by the fan on the gas to the work that would be done on an incompressible fluid with the same mass flow rate, inlet density and pressure ratio, taking into account the fan pressure as total pressure (k_p) or static pressure (k_{ps}).

The Regulation (EU) 327/2011 [10] establishes two methodologies to determine fan efficiency, both are defined to compute the overall fan system efficiency: the fan impeller, the transmission (gearbox), the electric motor and the variable speed drive, if any.

The first method applies to fan systems that are supplied as “final assembly”.

The second method applies to fan systems that are supplied as “not final assembly”, which needs one or more externally supplied components to be able to convert electric energy into fan gas power.

The two methods are described on the following sections.

4.4.1.Fan systems supplied as “final assembly”

Efficiency is calculated either per Equation 74 if the motor is direct on-line or Equation 75 if the motor is driven by a variable speed drive, both equations consider the fan operating at its optimal energy efficiency point.

$$\eta_e = \frac{P_{u(s)}}{P_e} \tag{74}$$

$$\eta_e = \frac{P_{u(s)}}{P_{ed}}.C_c \tag{75}$$

Where C_c is the part load compensation factor if motor is driven by a variable speed drive and may assume the following reference typical values:

$$C_c = \begin{cases} 1.04, & P_{ed} \geq 5\ kW; \\ -0.03\ln(P_{ed}) + 1.088, & P_{ed} < 5\ kW. \end{cases}$$

4.4.2. Fan systems supplied as “not final assembly”

Efficiency is calculated per Equation 76 considering the fan operating at its optimal energy efficiency point.

$$\eta_e = \eta_r . \eta_M . \eta_T . C_m . C_c \tag{76}$$

Where η_r is the fan impeller efficiency given by Equation 77.

$$\eta_r = \frac{P_{u(s)}}{P_a} \tag{77}$$

Where C_m is the compensation factor to account the components (mis)matching and may assume the typical value 0.9 suggested by Regulation (EU) 327/2011 [10]. This Regulation also provides the typical transmission efficiency in case it is a gearbox:

$$\eta_T = \begin{cases} 0.98, & P_a \geq 5\ kW; \\ 0.01.P_a + 0.93, & 1\ kW < P_a < 5\ kW; \\ 0.94, & P_a \leq 1\ kW. \end{cases}$$

4.4.3. Axial fan efficiency class determination

The minimum energy efficiency requirement for fans in the range 125 W to 500 kW are set by Commission Regulation (EU) 327/2011 [10] and since January 1st 2015 the limits of Table 9 are valid for axial fans.

Table 9 - Minimum energy efficiency requirement for fans [10]

Fan type	Measurement category (A-D)	Efficiency category (static or total)	Power range P (kW)	Target energy efficiency	Efficiency grade (N)
Axial fan	A, C	Static	0.125 ≤ P ≤ 10	$\eta_{target} = 2.74.\ln(P) - 6.33 + N$	40
			10 < P ≤ 500	$\eta_{target} = 0.78.\ln(P) - 1.88 + N$	
	B, D	Total	0.125 ≤ P ≤ 10	$\eta_{target} = 2.74.\ln(P) - 6.33 + N$	58
			10 < P ≤ 500	$\eta_{target} = 0.78.\ln(P) - 1.88 + N$	

The measurement and efficiency categories as defined previously in this chapter and P is the electrical input power P_e or P_{ed}.

The fan overall efficiency η_e calculated according to the appropriate method must be equal to or greater than the target value η_{target} set by the efficiency grade to meet the minimum energy efficiency requirements.

5. Methodology and Results

This chapter presents the method proposed by the author to meet this dissertation specific objectives and the outcoming results.

- Application of methodology described by IEC 61800-9-2 [7] and discussed in previous chapter to estimate the losses and efficiency at the 8 operating points suggested by this standard for a real Power Drive System with rated output power 132 kW, composed by a 132 kW rated power motor and a 312 A rated current CDM. The input data shall be the electric motor and CDM manufacturer's datasheets. Results are presented in sub-chapters 5.1 to 5.3.
- Initially this dissertation had a goal to determine the Energy Efficiency Index for the whole Extended Product with a real PDS and a real axial fan, based on the methodologies described by IEC 61800-9-2 [7] (for the PDS) and the Commission Regulation (EU) 327/2011 [10] (for the axial fan). However, due to the unavailability of axial fan parameters, this author proposes instead to compute the minimum axial fan efficiency to comply with Commission Regulation (EU) 327/2011 [10] using the real PDS efficiency at fan operating point. Sub-chapter 5.4 presents the results.
- Comparison of motor, CDM and PDS calculated losses with their respective reference losses given by IEC 61800-9-2 [7] to determine the CDM and PDS efficiency classification, as presented in sub-chapter 5.5.
- Comparison of calculated losses to measured losses on the real PDS with the objective to evaluate the feasibility of the calculation methodology proposed by IEC 61800-9-2 [7]. This final analysis is discussed in sub-chapter 5.6.

Electric motor and CDM manufacturer's datasheets are presented in Annex 1.

All parameters and symbols used in this chapter have already been defined in chapter 4.

5.1. Electric motor calculated efficiency

The methodology described in IEC 61800-9-2 [7] 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, this dissertation proposes to segregate the total loss at rated condition according to opposite procedure described by IEC 60034-2-1&3 [8] [9] and described in sub-chapter 4.1. While this standard intends to compute the total loss based on the segregated losses measurement, this dissertation proposes to segregate the losses based on the known value of total loss.

Table 10 presents the electric motor data extracted from the manufacturer datasheet [35].

Table 10 - Manufacturer data of electric motor 132 kW 4-pole IE3 400 VD 50 Hz [35]

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

Equation 78 is used to find motor input active power at rated condition and direct on-line supply.

$$P_{in,M@DOL} = \frac{P_{mec}}{\eta_{M@DOL}} = \frac{132000}{0.956} = 138075\ W \tag{78}$$

The manufacturer's test is corrected to a temperature +20ºC and datasheets also provided all data for +20ºC, therefore it is not required to correct the resistance and the slip because $k_\theta = 1.0$.

$$R_{Line(\Delta)}@20°\mathrm{C} = \frac{R_{Phase(\Delta)}@20°\mathrm{C}}{1.5} = 0.023\ \Omega \tag{79}$$

The no-load losses are given by Equation 80.

$$P_0 = \sqrt{3}.U_0.I_0.\cos\varphi_0 = 1491\ W \tag{80}$$

Considering $R_0 = R_{Line(\Delta)}@20°\mathrm{C}$ and applying the Equation 21 it is possible to find the constant losses and segregate it into core losses and friction and windage losses.

$$P_{Lcte} = P_0 - 1.5.R_0.I_0^2 = P_{Lfw} + P_{LFe} = 1391\ W \tag{81}$$

Two literature references are considered to segregate the constant losses, Table 11 shows the estimated proportion of core loss and friction and windage loss out of the total motor losses, according to each reference.

Table 11 - Electric motor constant losses composition

Author	**Core losses**	**Friction and windage losses**
IEC 60034-31 [29]	20-25% total losses	5-10% total losses
Litman et al. [30] Open enclosure, 1800 rpm, 100 HP	13% total losses	14% total losses
This dissertation	20% total losses 70% constant losses	10% total losses 30% constant losses

As the equation to compute part load losses are identical for core loss and friction and windage loss determination, this distribution shall not affect the final results. Therefore, this dissertation shall consider the arithmetic mean of both references without any deepest evaluation.

$$P_{LFe} = 70\%P_{Lcte} = 974\ W \tag{82}$$

$$P_{Lfw} = 30\%P_{Lcte} = 417\ W \tag{83}$$

Application of Equations 14 and 25 are meant to find stator and rotor winding losses.

$$P_{LS} = 1.5. R_{Line(\Delta)}@20℃. I_{in,M}^2 = 1809\ W \tag{84}$$

$$P_{LR} = \left(P_{in,M} - P_{LS} - P_{LFe}\right). s = 1258\ W \tag{85}$$

The Equation 27 is used to find residual loss which is considered identical to the additional load loss.

$$P_{LL} = P_{LRes} = P_{in,M} - P_{mec} - P_{LS} - P_{LR} - P_{Lfw} - P_{LFe} = 1617\ W \tag{86}$$

$$P_{L,M@DOL} = P_{LS} + P_{LR} + P_{Lfw} + P_{LFe} + P_{LL} = 6075\ W \tag{87}$$

IEC standard does not define any methodology to compute the harmonic losses based on analytical mathematics method, this dissertation considers the maximum harmonic losses defined by IEC 60034-30-2 [19] which depends on the CDM switching frequency:

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 4 kHz and recommended for motors with P_{mec} ≥ 90 kW.

The total losses with direct on-line supply shall be multiplied by the maximum harmonic factor to find the total losses of electric motor at CDM supply.

$$f_{sw} = 2\ kHz \xrightarrow{yields} r_H = 0.25 \tag{88}$$

$$P_{LH} = r_H. P_{L,M@DOL} = 1519\ W \tag{89}$$

$$P_{L,M@CDM} = P_{LH} + P_{L,M@DOL} = 7594\ W \tag{90}$$

The segregated losses at rated condition are summarized in Table 12 as Point 1 (f, T) = (100%, 100%).

Based on the segregated losses at rated condition, the Equations 35 to 46 are applied to compute the part load losses at points 2 to 8 as specified by IEC 61800-9-2 [7]. The results are presented in Table 12.

Table 12 - Electric motor segregated losses and calculated efficiency

Point		1	2	3	4	5	6	7	8
$f = \frac{f_{in,M@OP}}{f_{in,M}}$	%	100	100	50	50	50	10	10	10
$T = \frac{T_{mec@OP}}{T_{mec}}$	%	100	50	100	50	25	100	50	25
$P_{in,M@DOL}$	W	138075	68689	70195	34567	17410	16433	7593	3733
P_{mec}	W	132000	66000	66000	33000	16500	13200	6600	3300
P_{LSR}	W	3067	894	3067	894	350	3067	894	350
P_{LFe}	W	974	974	365	365	365	54	54	54
P_{Lfw}	W	417	417	156	156	156	23	23	23
$P_{LL} = P_{LRes}$	W	1617	404	606	152	38	89	22	6
$P_{L,M@DOL}$	W	6075	2689	4195	1567	910	3233	993	433
P_{LH}	W	1519	1519	1519	1519	1519	1519	1519	1519
$P_{L,M@CDM}$	W	7594	4208	5714	3086	2429	4752	2511	1951
$P_{L,M@CDM,Relative}$	%	5.8	3.2	4.3	2.3	1.8	3.6	1.9	1.5
$\eta_{M@CDM}$	%	**94.6**	**94.0**	**92.0**	**91.4**	**87.2**	**73.5**	**72.4**	**62.8**

5.2. CDM calculated efficiency

The CDM manufacturer datasheet (Annex 1) does not provide the constructive parameters to compute the losses as defined by IEC 61800-9-2, the known information is resumed in Table 13.

Table 13 - Manufacturer data of CDM 216 kVA 400 V 50 Hz [36]

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

From motor performance curve [35] it is possible to extract the motor absorbed current and displacement factor in function of relative load (relative torque-producing current), which is resumed in Table 14.

Table 14 - Test load current and displacement factor of the electric motor 132 kW 4-pole IE3 400 VD 50 Hz [35]

Load (%)	**100%**	**50%**	**25%**
Test load current $\frac{I_{in,M@OP}}{I_{in,M}}$	$\frac{229}{229} = 1.00$	$\frac{120}{229} = 0.52$	$\frac{90}{229} = 0.39$
Test load displacement factor $\cos \varphi_{M@OP}$	0.87	0.82	0.61

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

i. Calculation of CDM efficiency considering the typical parameters given by IEC 61800-9-2 [7].

ii. CDM efficiency provided by the manufacturer [36] in the 8 points specified by IEC 61800-9-2 [7].

To apply the first approach, the typical parameters considered for CDM efficiency calculation are presented in Table 15.

Table 15 - Typical CDM parameters according IEC 61800-9-2 [7]

CDM Part	Typical Parameters
Inverter	$U_{T,th} = 1.0\ V$ $U_{T,on} = 2.3\ V$ $U_{D,th} = 1.1\ V$ $U_{D,on} = 2.4\ V$ $E_T = 7.5.10^{-7}\ J/VA$ $E_D = 2.5.10^{-7}\ J/VA$ $U_{DC} = 540\ V$ $I_{motor\_cable} = 10\ A$
Diode Rectifier	$U_{D,th,rec} = 0.9\ V$ $U_{D,on,rec} = 2.2\ V$
Chokes	$k1_{choke} = 0.02$ $k2_{choke} = 0.25$
DC Link	$k1_{DC\_link} = 8.10^{-7}\ (\Omega A)^{-1}$ $k2_{DC\_link} = 2\ (\Omega A)$
Cable	$U_{rails} = 0.7\ V$
Control and Standby	$P_{L,control} = 50\ W$
Cooling	$k_{L,cooling} = 0.2$

Equations 54 to 65 are applied to compute the rated and part load losses at points 1 to 8 as specified by IEC 61800-9-2 [7]. The results are presented in Table 16.

Table 16 - CDM calculated losses and efficiency considering typical parameters given by IEC 61800-9-2 [7]

Point		1’	2’	3	4	5	6	7	8
$f = \frac{f_{in,M@OP}}{f_{in,M}}$	%	90	90	50	50	50	10	10	10
$T = \frac{T_{mec@OP}}{T_{mec}}$	%	100	50	100	50	25	100	50	25
$P_{L,on,T}$	W	189	73	152	59	37	115	45	30
$P_{L,on,D}$	W	24	12	63	27	22	102	41	29
$P_{L,sw,T}$	W	87	47	87	47	36	87	47	36
$P_{L,sw,D}$	W	29	16	29	16	12	29	16	12
$P_{L,inverter}$	W	1979	888	1989	893	645	2000	898	647
$P_{L,rectifier}$	W	959	343	404	159	79	55	25	14
$P_{L,choke}$	W	267	65	82	20	6	3	1	0
P_{L,DC_link}	W	158	93	99	79	75	74	73	73
$P_{L,rails}$	W	118	32	118	32	18	118	32	18
$P_{L,control}$	W	50	50	50	50	50	50	50	50
$P_{L,cooling}$	W	706	294	548	247	175	460	216	161
$P_{L,CDM}$	W	4236	1766	3290	1480	1047	2759	1296	963
$P_{L,CDM,Relative}$	%	2.0	0.8	1.5	0.7	0.5	1.3	0.6	0.4
η_{CDM}	%	**97.9**	**98.2**	**97.0**	**97.3**	**96.3**	**88.7**	**89.3**	**84.9**

Where Points 1 and Point 2 on Table 12 refers to f = 100% and Points 1’ and 2’ on Table 16 refers to f = 90%, due to reasons explained in the sub-chapter 4.2. This nomenclature is used on the whole extension of this dissertation.

The second approach considers the efficiency provided by the manufacturer [36] based on a cumulative experience and several tests performed on typical products. The efficiencies are shown in Table 17.

Table 17 - CDM losses and efficiency provided by the manufacturer [36]

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

5.3. PDS calculated efficiency

According to IEC 61800-9-2 [7], the total losses in PDS shall be the summation of motor and CDM losses with Equation 67 for the rated condition and 66 for part load operating points.

Table 18 shows the PDS calculated efficiency considering the first approach of CDM efficiency determination (CDM typical parameters given by IEC 61800-9-2 [7]).

Table 18 - PDS calculated losses and efficiency considering CDM typical parameters given by IEC 61800-9-2 [7]

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

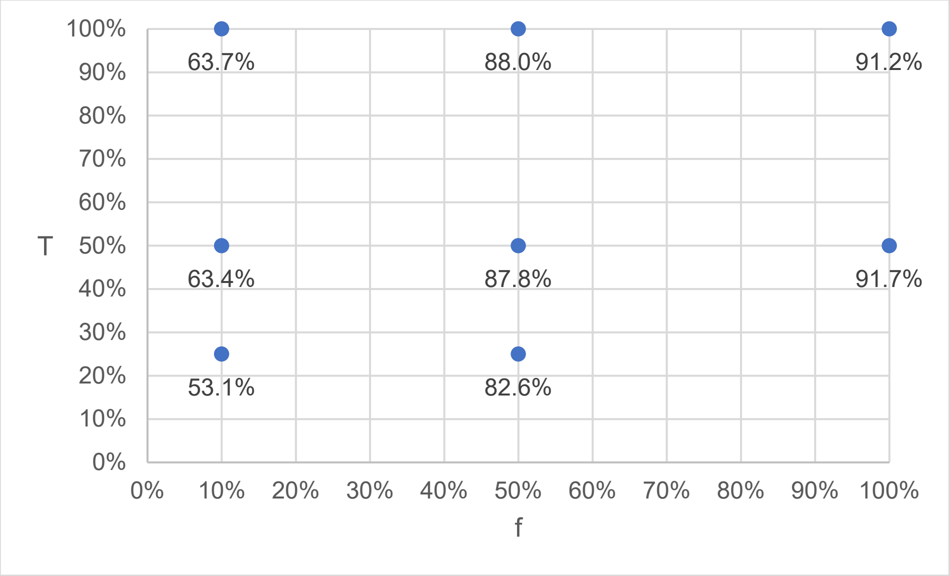


Figure 31 - PDS calculated efficiency considering CDM typical parameters given by IEC 61800-9-2 [7]

And Table 19 shows the PDS calculated efficiency considering the second approach of CDM efficiency (efficiency provided by the manufacturer).

Table 19 - PDS calculated losses and efficiency considering CDM efficiency provided by the manufacturer [36]

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

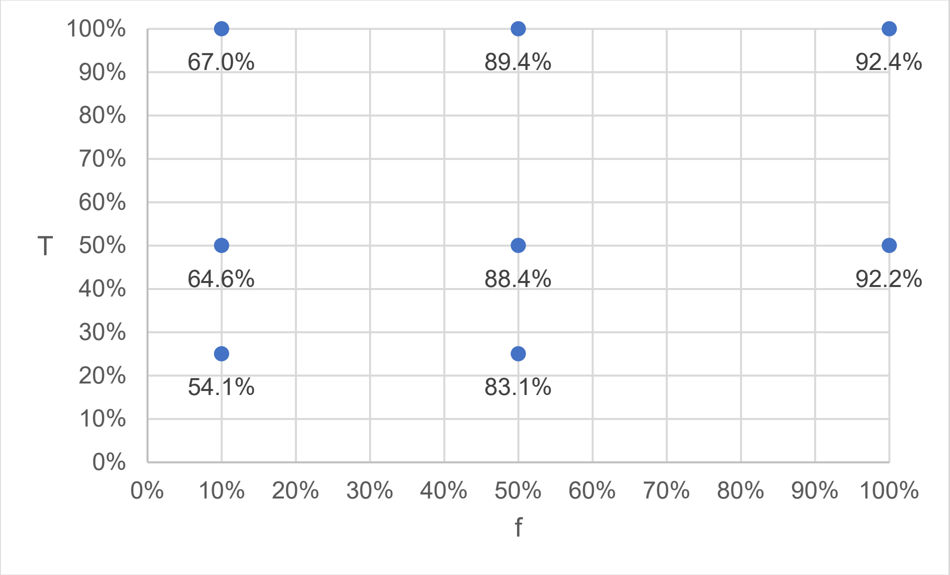


Figure 32 - PDS calculated efficiency considering CDM efficiency provided by the manufacturer [36]

5.4. Axial fan calculated efficiency

To calculate the axial fan efficiency, it is first required to find the PDS efficiency on the axial fan operating point. Fan operating point is provided by the fan manufacturer as given by Equation 91.

$$P_{mec@OP} = 120\ kW@\ 50\ Hz \tag{91}$$

$$f = \frac{f_{in,M@OP}}{f_{in,M}} = \frac{50}{50} = 100\% \tag{92}$$

$$T = \frac{T_{mec@OP}}{T_{mec}} = \frac{\frac{9550.P_{mec@OP}}{n_R}}{\frac{9550.P_{mec}}{n_R}} = \frac{120}{132} = 91\% \tag{93}$$

Hence, the load operating point is $(f, T) = (100\%, 91\%)$.

Based on the motor segregated losses at rated condition, the Equations 35 to 46 are applied to compute the motor efficiency at load operating point, the result is shown in Table 20.

From motor performance curve (Annex 1) it is possible to extract the motor absorbed current and displacement factor at load operating point.

$$\frac{I_{in,M@OP}}{I_{in,M}} = \frac{105}{229} = 0.90 \tag{94}$$

$$\cos\varphi_{M@OP} = 0.87 \tag{95}$$

Considering CDM typical parameters defined by IEC 61800-9-2 [7] (first approach), the Equations 54 to 65 are applied to compute the CDM efficiency and Equation 66 to compute PDS efficiency at load operating point, the result is shown in Table 20.

Table 20 - Motor, CDM and PDS calculated efficiency at fan operating point (first approach)

Point		Operating Point
$f = \frac{f_{in,M@OP}}{f_{in,M}}$	%	100
$T = \frac{T_{mec@OP}}{T_{mec}}$	%	91
$\eta_{M@CDM}$	%	94.6
η_{CDM}	%	98.0
η_{PDS}	%	92.0

Considering PDS efficiency at operating point, the PDS input power P_{ed} can be found by Equation 96.

$$P_{ed} = \frac{P_{mec@OP}}{\eta_{PDS@OP}} = \frac{120}{92.0\%} = 130.4\ kW \tag{96}$$

The fan test method A and PDS electric input power within the range 10 ≤ P_{ed} ≤ 500 kW leads to an Efficiency Grade $N = 40$ and a target efficiency as defined by Equation 97.

$$\eta_{target} = 0.78.\ln(P_{ed}) - 1.88 + N = 41.92\% \tag{97}$$

The fan overall efficiency η_e calculated according to method A must be equal or greater than the target value η_{target} set by the efficiency grade to meet the minimum energy efficiency requirement.

$$\begin{gathered}\eta_e \geq \eta_{target} \\ \eta_e \geq 41.92\%\end{gathered} \tag{98}$$

And the minimum axial fan efficiency is defined by Equation 99 which is equal to Equation 76 but $\eta_{PDS@OP}$ replaces η_m as the complete PDS efficiency on the operating point shall be considered.

$$\eta_e = \eta_r.\eta_{PDS@OP}.\eta_T.C_m.C_c \tag{99}$$

$$\eta_r \geq 49.67\% \tag{100}$$

Finally, the Energy Efficiency Index of the Extended Product (PDS, gearbox and axial fan) is at least 41.92% and the axial fan minimum efficiency to comply with Commission Regulation (EU) 327/2011 [10] is 49.67%.

Considering the CDM efficiency provided by the manufacturer (second approach), an interpolation shall be done on the PDS efficiency points closer to the load operating point to find the PDS efficiency at this point.

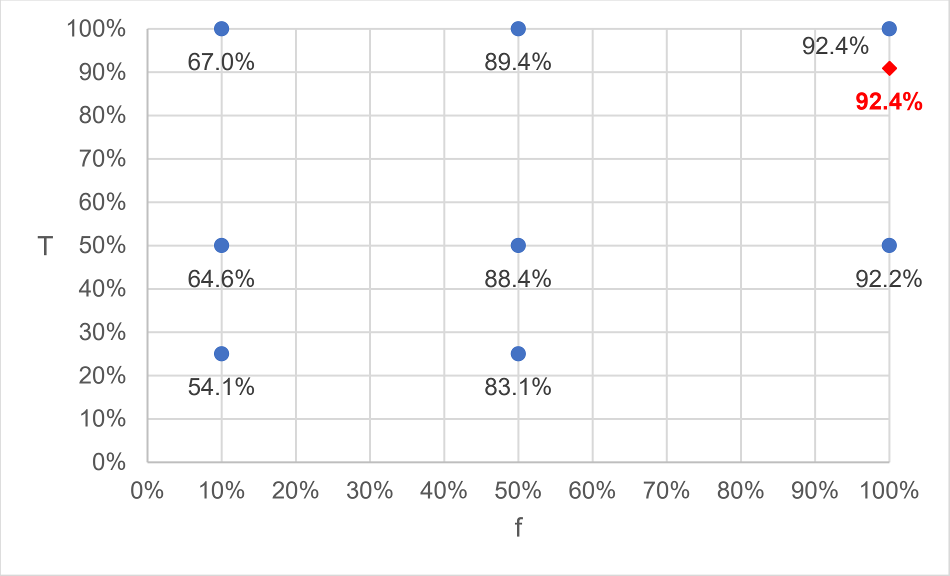


Figure 33 - PDS calculated efficiency at fan operating point (second approach)

According to Figure 33, the closer points are Point 1 (f,T) = (100%,100%) with PDS efficiency 92.4% and PDS losses 10875 W; and Point 2 (f,T) = (100%,50%) with PDS efficiency 92.2% and PDS losses 5603 W.

The interpolation method suggested by IEC 61800-9-2 [7] is presented in Equation 101 to 103.

$$P_{L,PDS@OP} = P_{L,PDS}(100\%,50\%) + \frac{P_{L,PDS}(100\%,100\%) - P_{L,PDS}(100\%,50\%)}{100\%T_{mec} - 50\%T_{mec}}.(T_{mec@OP} - 50\%T_{mec}) \tag{101}$$

$$P_{L,PDS@OP} = 5603 + \frac{10875 - 5603}{T_{mec}(1-0.5)}.T_{rated}(0.91 - 0.5) = 9917\ W$$

$$P_{L,PDS,Relative} = \frac{9917}{132000} = 7.5\% \tag{102}$$

$$\eta_{PDS@OP} = 92.4\% \tag{103}$$

Table 21 shows the motor, CDM and PDS calculated efficiency at fan operating point considering the CDM efficiency provided by the manufacturer and an interpolation between the closer given points.

Table 21 - Motor, CDM and PDS calculated efficiency at fan operating point (second approach)

Point		Operating Point
$f = \frac{f_{in,M@OP}}{f_{in,M}}$	%	100
$T = \frac{T_{mec@OP}}{T_{mec}}$	%	91
$\eta_{M@CDM}$	%	94.6
η_{CDM}	%	98.9
η_{PDS}	%	92.4

The PDS input power, and the target, overall and axial fan efficiency considering the second approach are given by Equations 104 to 107.

$$P_{ed} = \frac{P_{mec@OP}}{\eta_{PDS@OP}} = \frac{120}{92.4\%} = 129.9\ kW \tag{104}$$

$$\eta_{target} = 0.78.\ln(P_{ed}) - 1.88 + N = 41.92\% \tag{105}$$

$$\eta_e \geq 41.92\% \tag{106}$$

$$\eta_r \geq 49.47\% \tag{107}$$

The Energy Efficiency Index of the Extended Product (PDS, gearbox and axial fan) considering the second approach is at least 41.92% and the axial fan minimum efficiency to comply with Commission Regulation (EU) 327/2011 [10] is 49.47%.

5.5. Comparison between calculated losses and reference losses

This chapter presents the comparison between the calculated relative losses and the reference losses given by IEC 61800-9-2 [7] Annex A as well as the CDM and PDS efficiency classes.

5.5.1. Electric motor

Electric motor calculated losses compared to the 132 kW reference motor (RM) losses given by IEC 61800-9-2 [7] is shown in Table 22.

Table 22 - Electric motor relative losses compared to RM relative losses

Point		1	2	3	4	5	6	7	8
$f = \frac{f_{in,M@OP}}{f_{in,M}}$	%	100	100	50	50	50	10	10	10
$T = \frac{T_{mec@OP}}{T_{mec}}$	%	100	50	100	50	25	100	50	25
$P_{L,M@CDM,Relative}$	%	5.8	3.2	4.3	2.3	1.8	3.6	1.9	1.5
$P_{L,RM,Relative}$	%	7.0	3.9	4.6	2.5	1.9	3.2	1.4	1.0
$\frac{P_{L,M@CDM,Relative}}{P_{L,RM,Relative}}$	%	**82**	**82**	**94**	**94**	**97**	**112**	**136**	**148**

Table 22 shows that the 132 kW 4-pole IE3 400 VD 50Hz electric motor has 18% less losses at rated condition than the reference motor specified by IEC 61800-9-2 [7], considering losses based on calculated values.

This result was expected as the reference motor of IEC 61800-9-2 [7] 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 ratio between losses at rated condition of an IE3 and an IE2 class motor with DOL supply is 82%, which is the same as the calculated losses of Table 22.

The loss difference between an IE3 class motor and an IE2 class motor with DOL supply does not change if supplied by CDM.

5.5.2. Complete Drive Module (CDM)

The rated apparent output power of the CDM under analysis is between two reference values: 196 kVA and 245 kVA. The reference relative loss value with the next higher power rating shall be used for the IE class determination, as recommended by IEC 61800-9-2 [7]. Therefore, the CDM calculated losses are compared to the 245 kVA reference CDM losses given by this standard.

The comparison results are shown in Table 23 and Table 24 based on the two approaches of CDM losses calculation.

Table 23 - CDM relative losses (first approach) compared to RCDM relative losses

Point		1’	2’	3	4	5	6	7	8
$f = \frac{f_{in,M@OP}}{f_{in,M}}$	%	90	90	50	50	50	10	10	10
$T = \frac{T_{mec@OP}}{T_{mec}}$	%	100	50	100	50	25	100	50	25
$P_{L,CDM,Relative}$	%	2.0	0.8	1.5	0.7	0.5	1.3	0.6	0.4
$P_{L,RCDM,Relative}$	%	4.1	2.0	2.9	1.7	1.3	2.2	1.5	1.2
$\frac{P_{L,CDM,Relative}}{P_{L,RCDM,Relative}}$	%	**48**	**41**	**52**	**40**	**37**	**58**	**40**	**37**

CDM efficiency class based on rated condition comparison from Table 23:

$$\frac{P_{L,CDM,Relative}}{P_{L,RCDM,Relative}} = 48\% \Rightarrow IE2 \tag{108}$$

Table 23 shows that the 216 kVA 312 A CDM has 52% less losses at rated condition than the RCDM given by IEC 61800-9-2 [7], considering calculated losses based on typical parameters (first approach).

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

Table 24 - CDM relative losses (second approach) compared to RCDM relative losses

Point		1’	2’	3	4	5	6	7	8
$f = \frac{f_{in,M@OP}}{f_{in,M}}$	%	90	90	50	50	50	10	10	10
$T = \frac{T_{mec@OP}}{T_{mec}}$	%	100	50	100	50	25	100	50	25
$P_{L,CDM,Relative}$	%	1.1	0.7	1.0	0.6	0.4	0.8	0.5	0.4
$P_{L,RCDM,Relative}$	%	4.1	2.0	2.9	1.7	1.3	2.2	1.5	1.2
$\frac{P_{L,CDM,Relative}}{P_{L,RCDM,Relative}}$	%	**28**	**33**	**33**	**34**	**33**	**36**	**34**	**33**

CDM efficiency class based on rated condition comparison from Table 24:

$$\frac{P_{L,CDM,Relative}}{P_{L,RCDM,Relative}} = 28\% \;\Rightarrow IE2 \tag{109}$$

Table 24 based on CDM losses provided by the manufacturer [36] (second approach) presents better performance than the first approach, as it is based on real parameters. The CDM has 72% less losses at rated condition than the reference CDM specified by IEC 61800-9-2 [7] and therefore it is classified as IE2.

5.5.3. Power Drive System (PDS)

The PDS calculated losses are compared to the 132 kW reference PDS (RPDS) losses given by IEC 61800-9-2 [7] and shown in Table 25 and Table 26 based on the first and second approaches respectively of CDM losses calculation.

Table 25 - PDS relative losses (first approach) compared to RPDS relative losses

Point		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
$f = \frac{f_{in,M@OP}}{f_{in,M}}$	%	100	100	50	50	50	10	10	10
$T = \frac{T_{mec@OP}}{T_{mec}}$	%	100	50	100	50	25	100	50	25
$P_{L,PDS,Relative}$	%	9.6	4.5	6.8	3.5	2.6	5.7	2.9	2.2
$P_{L,RPDS,Relative}$	%	12.8	6.4	8.2	4.6	3.5	6.0	3.2	2.5
$\frac{P_{L,PDS,Relative}}{P_{L,RPDS,Relative}}$	%	**75**	**71**	**83**	**75**	**75**	**95**	**90**	**88**

PDS efficiency class based on rated condition comparison from Table 25:

$$\frac{P_{L,PDS,Relative}}{P_{L,RPDS,Relative}} = 75\% \;\Longrightarrow IES2 \tag{110}$$

Table 25 shows that the 132 kW PDS has 25% less losses at rated condition than the reference value of IEC 61800-9-2 [7], considering CDM calculated losses based on typical parameters (first approach).

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).

Table 26 - PDS relative losses (second approach) compared to RPDS relative losses

Point		1	2	3	4	5	6	7	8
$f = \frac{f_{in,M@OP}}{f_{in,M}}$	%	100	100	50	50	50	10	10	10
$T = \frac{T_{mec@OP}}{T_{mec}}$	%	100	50	100	50	25	100	50	25
$P_{L,PDS,Relative}$	%	8.2	4.2	5.9	3.3	2.5	4.9	2.7	2.1
$P_{L,RPDS,Relative}$	%	12.8	6.4	8.2	4.6	3.5	6.0	3.2	2.5
$\frac{P_{L,PDS,Relative}}{P_{L,RPDS,Relative}}$	%	**64**	**66**	**72**	**71**	**73**	**82**	**85**	**85**

PDS efficiency class based on rated condition comparison from Table 26:

$$\frac{P_{L,PDS,Relative}}{P_{L,RPDS,Relative}} = 64\% \implies IES2 \tag{111}$$

PDS losses provided in Table 26 based on CDM losses provided by the manufacturer [36] (second approach) presents better performance than the first approach, as it is based on real parameters. The PDS has 36% less losses at rated condition than the reference PDS specified by IEC 61800-9-2 [7] and therefore it is classified as IES2.

5.6. Comparison between calculated losses 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 CDM were tested together in a string test with input-output measurement setup as determined by IEC 61800-9-2 [7] and the measured losses / efficiency were compared to the losses / efficiency determined by the methodology.

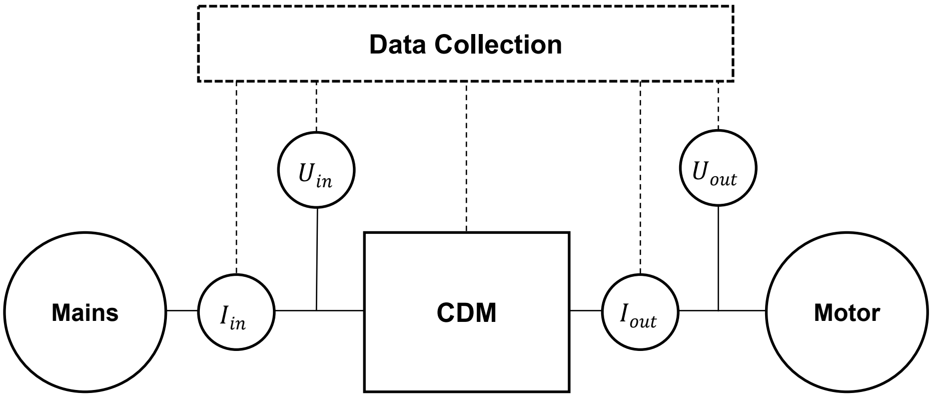


Figure 34 - Input-output measurement setup for CDM losses determination [7]

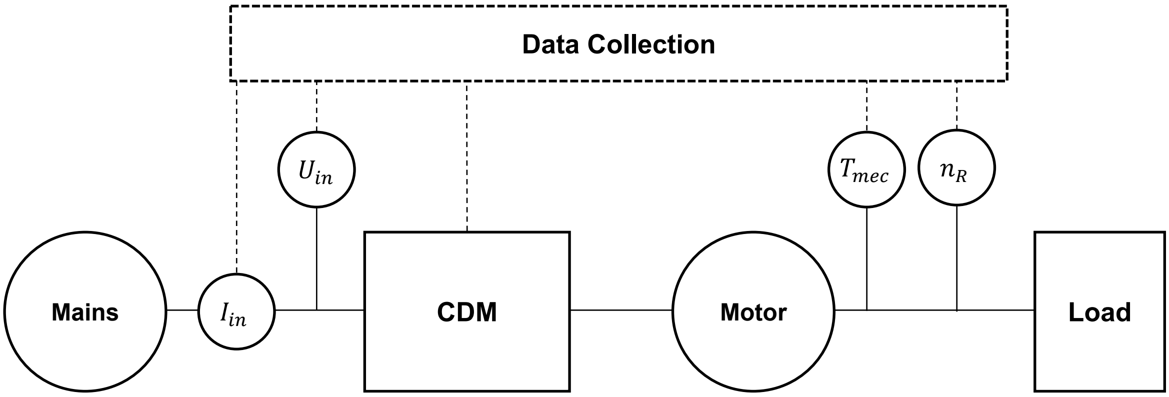


Figure 35 - Input-output measurement setup for PDS losses determination [7]

The measured values are presented in Table 27. All measurements are RMS values and parameters in and out take CDM as reference. Motor output power P_{mec} was calculated based on measured output torque and speed by Equation 11.

Table 27 - String test measured results

Point		**1**	**2**	**1'**	**2'**	**3**	**4**	**5**	**6**	**7**	**8**
$f = \frac{f_{in,M@OP}}{f_{in,M}}$	%	100	100	90	90	50	50	50	10	10	10
$T = \frac{T_{mec@OP}}{T_{mec}}$	%	100	50	100	50	100	50	25	100	50	25
$P_{in,CDM}$	kW	141.9	71.4	127.5	64.0	73.0	36.3	19.0	16.9	8.4	4.5
$P_{out,CDM}$	kW	139.5	70.2	125.2	62.8	70.9	35.3	18.5	15.5	7.7	4.0
$T_{mec@OP}$	Nm	853	427	849	425	850	424	214	849	425	212
$n_{R@OP}$	rpm	1487	1495	1337	1345	736	744	748	140	147	149
$P_{mec@OP}$	kW	132.9	66.9	118.8	59.8	65.5	33.0	16.8	12.5	6.5	3.3

Motor losses are given by the difference between CDM output active power $P_{out,CDM}$ and motor mechanical power $P_{mec@OP}$. Relative motor losses are calculated by Equation 44 as a percentage of motor rated power 132 kW and efficiency is computed by Equation 12 as the ratio of motor input power that is converted into mechanical power at motor shaft.

Similarly, CDM losses are given by the difference between CDM input active power $P_{in,CDM}$ and CDM output active power $P_{out,CDM}$. Relative CDM losses are calculated by Equation 65 as a percentage of CDM rated power 216 kVA and efficiency is computed as the ratio of CDM input active power that is converted into output active power.

Finally, PDS losses are given by the difference between the CDM input active power $P_{in,CDM}$ and motor mechanical power $P_{mec@OP}$. Relative PDS losses are calculated as a percentage of PDS rated power 132 kW and the efficiency is computed as the ratio of CDM input active power that is converted into motor mechanical power.

The relative losses and efficiency based on measured values are presented in Table 28.

Table 28 - Relative losses and efficiency based on measured results

Point		1	2	1’	2’	3	4	5	6	7	8
$f = \frac{f_{in,M@OP}}{f_{in,M}}$	%	100	100	90	90	50	50	50	10	10	10
$T = \frac{T_{mec@OP}}{T_{mec}}$	%	100	50	100	50	100	50	25	100	50	25
$P_{L,M@CDM}$	W	6660	3334	6358	3030	5461	2339	1657	3080	1143	720
$P_{L,M@CDM,Relative}$	%	5.0	2.5	4.8	2.3	4.1	1.8	1.3	2.3	0.9	0.5
$\eta_{M@CDM}$	%	95.2	95.3	94.9	95.2	92.3	93.4	91.0	80.2	85.1	82.1
$P_{L,CDM}$	W	2360	1140	2320	1150	2030	1001	594	1410	700	430
$P_{L,CDM,Relative}$	%	1.1	0.5	1.1	0.5	0.9	0.5	0.3	0.7	0.3	0.2
η_{CDM}	%	98.3	98.4	98.2	98.2	97.2	97.2	96.9	91.7	91.6	90.3
$P_{L,PDS}$	W	9020	4474	8678	4180	7491	3340	2251	4490	1843	1150
$P_{L,PDS,Relative}$	%	6.8	3.4	6.6	3.2	5.7	2.5	1.7	3.4	1.4	0.9
η_{PDS}	%	93.6	93.7	93.2	93.5	89.7	90.8	88.2	73.5	78.0	74.2

Figure 36 presents the comparison between motor calculated losses according to proposed methodology and the measured losses. The error as a proportion of measured result is given by Equation 112.

$$Error = \frac{P_{L,Calculated} - P_{L,Measured}}{P_{L,Measured}} . 100\% \qquad (112)$$

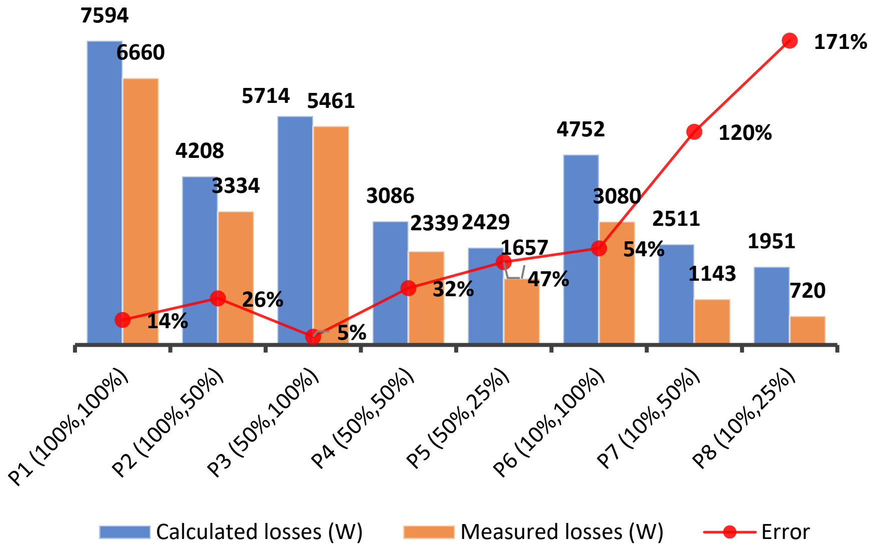


Figure 36 - Comparison between calculated losses and measured losses – Electric Motor

The difference between calculated and measured losses for motors is 14% at rated condition (934 W) and the error increases for part load conditions (except for Point 3), particularly for operating points with 10% frequency.

Motor losses with direct on-line supply were also measured to validate the datasheet values. Direct on-line measured results are given only at rated speed because motors cannot variate the speed without a VSD. The result is shown in Table 29.

Table 29 - Direct on-line test measured results of electric motor 132 kW 4-pole IE3 400 VD 50 Hz

$T = \frac{T_{mec@OP}}{T_{mec}}$	$P_{in,M@DOL}$	$P_{mec@OP}$	$I_{in,M@OP}$	$T_{mec@OP}$	$n_{R@OP}$	$\cos\varphi_{M@OP}$	$\eta_{M@DOL}$
%	kW	kW	A	N.m	rpm	-	%
10	14.76	13.20	52.57	79.30	1499	0.41	89.40
20	28.11	26.40	67.96	165.15	1498	0.60	93.90
30	41.53	39.60	84.41	250.67	1496	0.71	95.40
40	55.00	52.80	101.88	335.94	1495	0.78	96.00
50	68.56	66.00	120.36	421.05	1494	0.82	96.30
60	82.19	79.20	139.84	506.08	1492	0.85	96.40
70	95.92	92.40	160.30	591.10	1491	0.86	96.30
80	109.76	105.60	181.73	676.20	1489	0.87	96.20
90	123.70	118.80	204.10	761.45	1487	0.87	96.00
100	137.75	132.00	227.41	846.94	1486	0.87	95.80
110	151.94	145.20	251.63	932.75	1484	0.87	95.60
120	166.26	158.40	276.75	1018.96	1482	0.87	95.30
130	180.72	171.60	302.75	1105.64	1480	0.86	95.00
140	195.33	184.80	329.62	1192.88	1478	0.86	94.60
150	210.10	198.00	357.35	1280.77	1475	0.85	94.20

One can notice 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. Table 29 presents the measured DOL motor loss of 5750 W at 100% torque and the electric motor datasheet [35] (Annex 1) presents the DOL motor loss of 6075 W at 100% torque. Therefore, 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 [7] nor IEC 60034-2-3 [9] 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.

Figure 37 and Figure 38 present the comparison between CDM measured losses and CDM calculated losses according to proposed methodology, considering the two approaches: (i) CDM typical parameters given by IEC 61800-9-2 [7] and (ii) CDM losses provided by the manufacturer [36]. The errors are calculated by Equation 112.

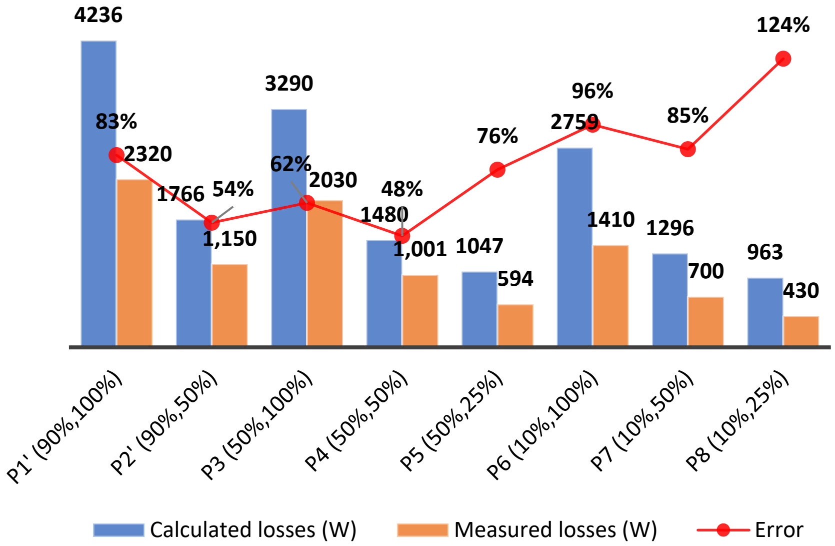


Figure 37 - Comparison between calculated losses and measured losses – CDM first approach

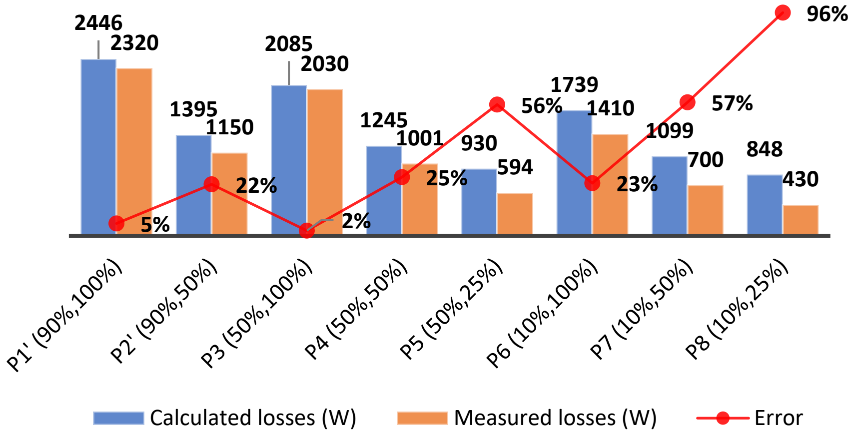


Figure 38 - Comparison between calculated losses and measured losses – CDM second approach

Graphs in Figure 37 and Figure 38 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 Figure 38, 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 of Figure 38 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 Figure 38 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 Figure 37, which makes the proposed methodology inaccurate as it should at least present the same trend.

This 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 [7] allows measurement tolerance up to 12 Hz on Points 6, 7 and 8.

Figure 39 and Figure 40 present the comparison between PDS measured losses and PDS calculated losses according to proposed methodology, considering the two approaches: (i) CDM typical parameters given by IEC 61800-9-2 [7] and (ii) CDM losses provided by the manufacturer [36]. The errors are calculated by Equation 112.

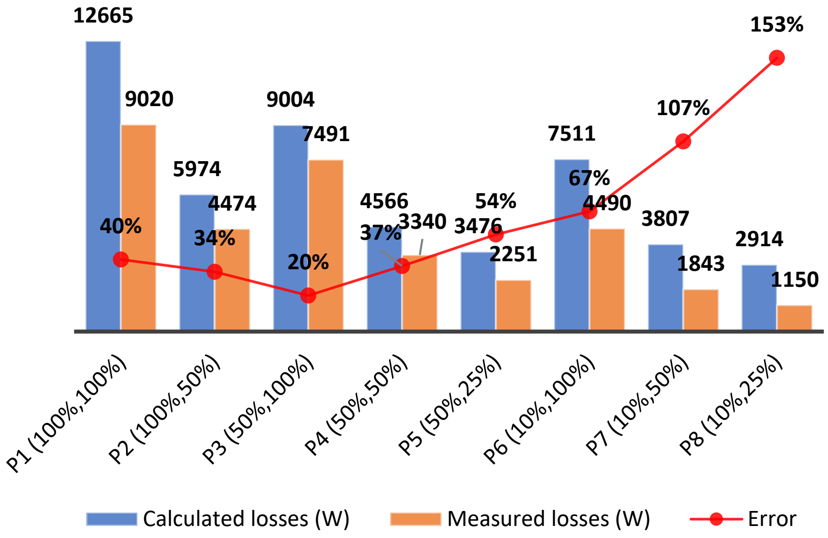


Figure 39 - Comparison between calculated losses and measured losses – PDS (CDM first approach)

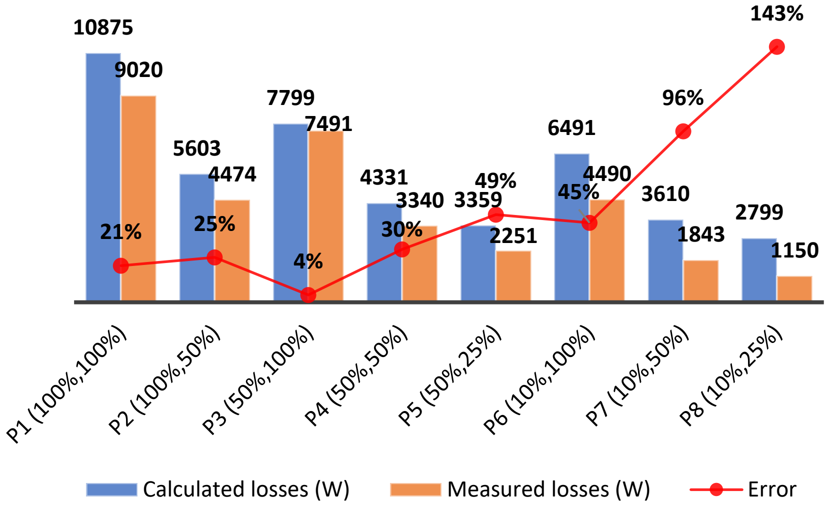


Figure 40 - Comparison between calculated losses and measured losses – PDS (CDM second approach)

Graphs in Figure 39 and Figure 40 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.

Figure 39 shows that the high errors from CDM first approach calculation (Figure 37) 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.

Figure 40 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 67. If this factor were not considered, the error at Point 1 would be 11%.

As the measurements were done on Points 1 (100%,100%) and 1' (90%,100%), it is possible to check if the correction factor should be really required on the computation method. By taking into consideration the motor measured losses at Point 1, which is 6660 W, multiplied by correction factor k_{VD} = 1.11, and summed to CDM losses at Point 1', which is 2320 W, the total would be 9712 W. That is far too high when compared to the PDS measured losses at Point 1, which is 9020 W.

In other way around, if this total amount 9712 W is compared to PDS calculated loss at Point 1 of Figure 40, which is 10875 W, it would represent 12% of error at rated condition, approximately the same error that would appear if the correction factor was not applied.

There is a possibility that the comparison at PDS rated condition has not been done properly once the calculated PDS losses at Point 1 considers the correction factor but the measured PDS losses at Point 1 does not consider any correction factor (and consider CDM losses at 100% frequency). In any case, this analysis shows that at least for this specific PDS, the correction factor brings an additional error for the rated condition computation losses.

6. Conclusion

6.1. Specific conclusion

The main objective of this dissertation was the analysis and discussion about the Ecodesign standard IEC 61800-9 [6] [7], since the new Regulation (EU) 1781/2019 [5] will enter into force next year (2021) making it mandatory for the Power Drive System manufacturers to apply the Extended Product Approach described by IEC 61800-9 [6] [7] to define the energy efficiency of their products at eight operating points defined by this standard.

Standard IEC 61800-9 [6] [7] is a complete analysis of the Extended Product composed of an electric motor, its Complete Drive Module (variable speed drive and its auxiliaries) and its driven machine (load machine and transmission). This standard proposes a Semi-Analytical Model to compute the efficiency of the Power Drive System 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.

The author proposed to apply the Semi-Analytical-Model presented by IEC 61800-9-2 [7] to a real PDS, composing of an AC three-phase squirrel cage electric motor 132 kW 4-pole IE3 400 VD 50 Hz [35] and a stand-alone variable speed drive 216 kVA 312 A 400 VD 50 Hz [36], 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 a methodology to segregate the total rated losses based on standard IEC 60034-2-1&3 [8] [9]. The segregated losses results were acceptable as the proportion of each motor loss were approximately what are presented by the literature [29] and [30].
- The CDM datasheet does not provide the relevant parameters for CDM losses calculation. To overcome this issue, the author proposed two approaches: (i) compute the CDM losses based on typical parameters provided by IEC 61800-9-2 [7] and (ii) use the CDM losses provided by the manufacturer [36].

The comparison between the computed losses and the reference losses for the motor, CDM and PDS provided by IEC 61800-9-2 [7] resulted in better performance on the 8 operating points. The motor was expected to have lower losses than the reference motor, as the motor under analysis is IE3 and the reference losses are based on IE2 efficiency class. For the CDM, the calculated losses at rated condition was 48% of the reference CDM losses considering the first approach (i), and 28% of the reference CDM losses considering the second approach (ii), which means this CDM is classified as IE2 efficiency class, complying to Regulation (EU) 1781/2019 [5]. For the PDS, the calculated losses at rated condition was 75% of the reference PDS losses considering the first approach (i), and 64% of the reference PDS losses considering the second approach (ii), leading this PDS to IES2 efficiency class.

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. That is a common practice on the majority of industries and manufacturers due to the measurement instruments uncertainties that has to be considered at its worst condition. That should not be higher than the tolerance accepted by the standard, which is 15% for efficiency values, according to IEC 60034-1 [37]. The comparison between datasheet and measurement at DOL condition presented an error of 5% at rated condition and 4% at Point 2 (100% frequency, 50% torque) due to this factor, therefore within the expected tolerance.
- Proposed methodology considers the harmonic losses at its maximum allowed value as neither the IEC 61800-9-2 [7] nor IEC 60034-2-3 [9] give any methodology to estimate the real harmonic losses. That represent an error equal to 609 W (9%) at rated condition and is basically constant in part load conditions, representing more in percentage values once other losses are lower.
- 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. This could be not true to very low frequency conditions as the voltage is also very low which could lead to lower harmonic absolute losses.

For CDM the calculation method presented an error at rated condition of 83% and 5% in the first and second approach, respectively. Comparing the errors at part load condition of first and second approach 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. Therefore, this author suggests as a future research that the proposed methodology described by IEC 61800-9-2 [7] for the CDM should be repeated but using the real CDM parameters.

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).

A special remark was made about the additional error on PDS loss computation due to the correction factor multiplying motor losses at rated condition. Therefore, this author suggests as future research the check of real impact of this correction factor on other PDS ratings. This author questions the reason why IEC 61800-9-2 [7] recommends the use of this correction factor on the calculation method but not on the measurement losses determination.

The absolute motor losses represent approximately two times the absolute losses of the CDM. Therefore, a more precise calculation of motor harmonic losses shall impact positively on PDS losses calculation, particularly at part load conditions, what could compensate the errors on CDM calculated losses.

To complement this dissertation study, it was expected to compute the Energy Efficiency Index of a complete Extended Product, considering a real axial fan and gearbox as the driven equipment. However, it was not possible to acquire the real axial fan parameters as operating pressure, volume flow rate and gas properties, preventing the feasibility of the complete extended analysis. Nevertheless, the author proposed instead to compute the minimum efficiency required by an axial fan coupled to the PDS under analysis to comply to Commission Regulation (EU) 327/2011 [10].

Considering the CDM’s typical parameters given by IEC 61800-9-2 [7], the PDS efficiency at operating point of the axial fan computed according to proposed methodology is 92.0%. That led to an Energy Efficiency Index for the Extended Product of at least 41.92% and an axial fan efficiency of minimum 49.67% to comply with Regulation (EU) 327/2011 [10].

Considering the second approach (CDM losses provided by the manufacturer), an interpolation was done between the closest points of the axial fan operating point to find the PDS efficiency of 92.4% at the load operating point. This PDS efficiency led to an Energy Efficiency Index for the Extended Product of at least 41.92% (the same) and an axial fan efficiency of minimum 49.47% to comply with Regulation (EU) 327/2011 [10].

6.2. General conclusion

The Ecodesign standard IEC 61800-9 [6] [7] 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 (MEPS).

Although, this dissertation discussed that the practical application of the methodology described by IEC 61800-9 [6] [7] 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 [6] [7] 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.

6.3. Future topics

Throughout this dissertation the author suggested topics for future research:

- Application of proposed methodology with CDM and load machine real constructive parameters.
- Extension of proposed methodology for other types of CDMs (complete panels with external filters or other drives configurations as active front end) and load machines (pumps, compressors, converters, etc.).
- Analysis of the impact on PDS rated losses of using the correction factor k_{VD} in Equation 67, considering a broader sample.
- Methodology to determine harmonics losses in electric motors.
- Impact assessment of the Regulation (EU) 1781/2019 [5], approaching the energy savings forecast and results.
- Comparison of energy savings by using MEPS for system, as Regulation (EU) 1781/2019 [5], and MEPS for standalone products, as Regulation (EC) No 640/2009.

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Annex 1

DATA SHEET

Three Phase Induction Motor - Squirrel Cage

Customer	: WEG BENELUX S.A.
Sales document	: 50545131 - 000010
Product line	: W22 - IE3 Premium Efficiency Ip/In <= 6

Frame	: 315S/M
Output	: 132 kW
Poles	: 4
Frequency	: 50 Hz
Rated voltage	: 400 V
Rated current	: 229 A
L. R. Amperes	: 1374 A
LRC (p.u.)	: 6.0
No load current	: 53.8 A
Rated speed	: 1486 rpm
Slip	: 0.93 %
Rated torque	: 849 Nm
Locked rotor torque	: 190 %
Pull up torque	: 160 %
Breakdown torque	: 200 %
Insulation class	: F
Service factor	: 1.00
Moment of inertia (J)	: 4.42 kgm²

Locked rotor time	: 45 s (hot) 81 s (cold)
Temperature rise4	: 80 K
Duty cycle	: S1
Ambient temperature	: -20 ℃ to +40 ℃
Altitude	: 1000 m.a.s.l
Degree of protection	: IP55
Cooling method	: IC411 - TEFC
Mounting	: B3T
Direct of rotation¹	: Both
Noise level²	: 71.0 dB(A)
Starting method	: VFD
Approx. weight³	: 1215 kg
Design	: N

Output	Start	25%	50%	75%	100%
Efficiency (%)	-	93.6	95.4	95.5	95.6
Power factor	0.37	0.61	0.82	0.86	0.87

Load type	: Parabolic torque
Load torque	: 849 Nm
Load inertia (J=GD²/4)	: 14.75 kgm²

Operation limits with inverter
5 Hz up to 50 Hz (Variable torque): 849 Nm

Maximum peak voltage phase-to-phase	<= 1600 V
dV/dt	<= 5200 V/µs
Rise time	>= 0,1 µs

	Drive end	Non drive end
Bearing type	6319-C3	6316-C3
Lubrication interval	11000 h	13000 h
Lubricant amount	45 g	34 g
Lubricant type	MOBIL POLYREX EM	

Foundation loads

Maximum traction	: 7407 N
Maximum compression	: 19326 N

Notes:
W22Xec IE3 IIC T3 Gc
Sound pressure level with 119.5 kW load <= 80 dB(A) + 0 tol (DOL)
Number of consecutive starts (hot): 7 (100%Un) / 6 (80%Un)
Number of starts per hour (hot): 7 (100%Un) / 6 (80%Un)

Standards

Specification	: IEC 60034-1	Vibration	: IEC 60034-14
Tests	: IEC 60034-2	Tolerance	: IEC 60034-1
Noise	: IEC 60034-9		

This revision replaces and cancels the previous one, which must be eliminated.

(1) When viewed from the drive end.
(2) Measured at 1m and with tolerance of +3dB(A).
(3) Approximate weight subject to changes after manufacturing process.
(4) At the rated point.

These are average values based on tests with sinusoidal power supply, subject to the tolerances stipulated in IEC 60034-1.

Rev.	Summary of changes	Performed	Checked	Date

Performed by	lcorrea	378866/2019	
Checked by	AUTOMATICO	Page	Revision
Date	05/03/2020	1/1	2

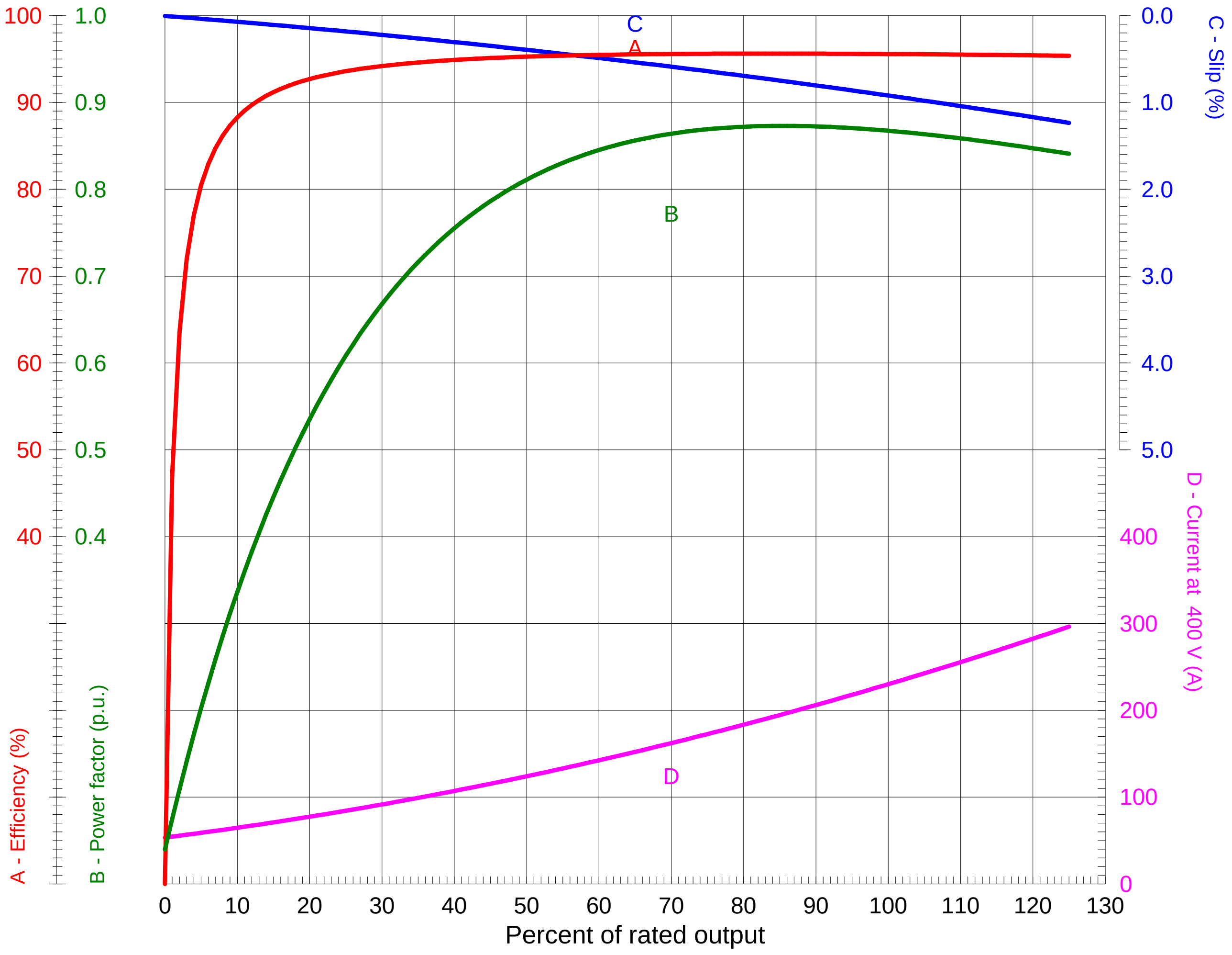
LOAD PERFORMANCE CURVE

Three Phase Induction Motor - Squirrel Cage

Customer : WEG BENELUX S.A.

Sales document : 50545131 - 000010

Product line : W22 - IE3 Premium Efficiency Ip/In <= 6



Performance : 132 kW 400 V 50 Hz 4P 315S/M

Rated current	: 229 A	Moment of inertia (J)	: 4.42 kgm²
LRC (p.u.)	: 6.0	Duty cycle	: S1
Rated torque	: 849 Nm	Insulation class	: F
Locked rotor torque	: 190 %	Service factor	: 1.00
Breakdown torque	: 200 %	Temperature rise	: 80 K
Rated speed	: 1486 rpm	Design	: N

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EQUIVALENT CIRCUIT

Three Phase Induction Motor - Squirrel Cage

Customer : WEG BENELUX S.A.

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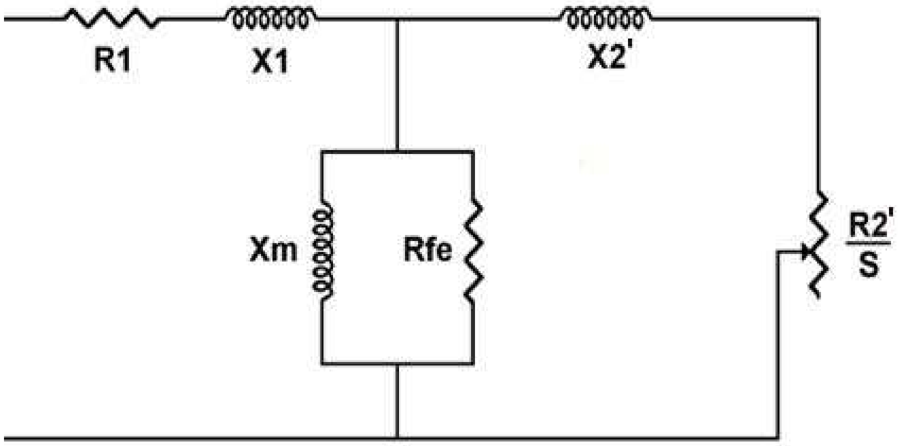
Product line : W22 - IE3 Premium Efficiency Ip/In <= 6



Rated			
R1	0.0345 ohms / 0.0285 p.u.	**X1**	0.2980 ohms / 0.2459 p.u.
R2'	0.0223 ohms / 0.0184 p.u.	**X2'**	0.5530 ohms / 0.4562 p.u.
Rfe	531.7440 ohms / 438.6965 p.u.	**Xm**	12.3110 ohms / 10.1568 p.u.

Locked rotor			
R1	0.0357 ohms / 0.0295 p.u.	**X1**	0.2780 ohms / 0.2294 p.u.
R2'	0.1685 ohms / 0.1390 p.u.	**X2'**	0.2490 ohms / 0.2054 p.u.
Rfe	348.0930 ohms / 287.1818 p.u.	**Xm**	13.0700 ohms / 10.7829 p.u.

T"do	1.4295 s	**X/R**	9.6443 p.u.
T"d	0.0598 s	**RS**	0.0145 ohms / 0.0120 p.u.
Ta	0.0307 s	**X"d = Xs**	0.5279 ohms / 0.4355 p.u.
Zbase	1.2121 ohms	**X2(-)**	0.3519 ohms / 0.2903 p.u.

All parameters reflected to stator side.
Per phase values, for connection.
Resistances at 20.0 ℃, reactances at rated voltage and frequency.

Performance : 132 kW 400 V 50 Hz 4P 315S/M

R1 = Stator resistance
R2' = Rotor resistance
Rfe = Core loss resistance
X1 = Stator leakage reactance
X2' = Rotor leakage reactance
Xm = Magnetizing reactance
Zbase = Base impedance

T"do = Open circuit AC time constant
T"d = Short circuit AC time constant
Ta = Short circuit DC time constant
X/R = X/R Ratio
RS = Supplementary losses resistance
X"d = Xs = Subtransient reactance
X2(-) = Negative sequence reactance

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DATASHEET

Variable Speed Drives

Main Features

Reference	: EUCFW110312T4SZ
Product code	: 11374887
Product line	: CFW11

Basic data

Power supply	: 380-480 V
Input minimum-maximum voltage	: 323-528 V
Number of phases	
Input	: 3
Output	: 3

Supply voltage range	380-480 V		380-480 V	
Overload regime	Normal (ND)	Heavy (HD)	Normal (ND)	Heavy (HD)
Rated current	312A	242		
Overload current at 60 s	343A	343A		
Overload current at 3 s	468A	500		

Maximum applicable motor

Voltage/Frequency	Power (HP / kW) [1]	
	Normal Overload (ND)	Heavy Overload (HD)
380V / 50Hz	220 / 160	150 / 110
380V / 60Hz	200 / 150	150 / 110
400V / 50Hz	220 / 160	175 / 132
400V / 60Hz	200 / 150	150 / 110
440V / 50Hz	250 / 185	200 / 150
440V / 60Hz	250 / 185	200 / 150
460V / 60Hz	270 / 200	200 / 150
480V / 60Hz	270 / 200	200 / 150

Dynamic braking [2]	: Standard without braking
Electronic supply	: Internal
Safety Stop	: No
RFI internal filter [3]	: With filter (C3 category)
External filter	: Not available
Link Inductor	: Yes
Memory card	: Included in the product
USB port	: Standard in the product
Line frequency	: 50/60Hz
Line frequency range (minimum - maximum)	: 48-62 Hz
Phase unbalance	: Less or equal to 3% of input rated line voltage
Transient voltage and overvoltage	: Category III
Rated current of single-phase input	
- Overload (ND)	:
- Overload (HD)	:
Rated current of three-phase input	
- Overload (ND)	: 312A
- Overload (HD)	: 242A
Power factor	: 0,94
Displacement factor	: 0,98
Rated efficiency	: ≥ 98%
Maximum connections (power up cycles - on/off) per hour	: 60
DC power supply	: Not allow
Standard switching frequency	
- Overload ND	: 2,5 kHz
- Overload HD	: 2,5 kHz
Selectable switching frequency	: 1,25; 2; 2,5 and 5 kHz
Real-time clock	: Yes, in the HMI
COPY Function	: Yes, by HMI/MMF
Dissipated power:	

Mounting type	Overload		Overload (*)	
	ND	HD	ND	HD
Surface	3957 W	3046 W	Not applicable	Not applicable
Flange	826 W	614 W	Not applicable	Not applicable

Source available to the user

Output voltage	: 24 Vcc
Maximum capacity	: 500 mA

Control/performance data
Power supply : Switched-mode power supply
Control method : V/f, VVW, Vector and PM motor
Encoder interface : Only with 'Slot 2' accessory
Control output frequency : 0 to 300 Hz
Frequency resolution : Equivalent to 1 rpm
V/F Control
- Speed resolution : 1% of rated speed
- Speed range : 1:20

VVW Control
- Speed resolution : 1% of rated speed
- Speed range : 1:30

Sensorless vector control
- Speed resolution : 0,5% of rated speed
- Speed range : 1:100

Vector control with encoder
- Speed resolution : 0,05% of rated speed
- Speed range : Up to 0 rpm

Analog inputs
Quantity (standard) : 2
Levels : 0-10V, 0/4-20mA and -10-+10V
Impedance
- Impedance for voltage input : 400 kΩ
- Impedance for current input : 500 Ω

Function : Programmable
Maximum allowed voltage : ±30 Vcc

Digital inputs
Digital inputs - Quantity (standard) : 6
Activation : Active low and high
Maximum low level : 3 V
Minimum high level : 18 V
Input current : 11 mA
Maximum input current : 13,5 mA
Function : Programmable
Maximum allowed voltage : 30 Vcc

Analog outputs
Analogic outputs - Quantity (standard) : 2
Levels : 0 to 10V, 0 to 20mA and 4 to 20mA
RL for voltage output : 10 kΩ
RL for current output : 500 Ω
Function : Programmable

Digital outputs
Digital outputs - Quantity (standard) : 3 NO/NC relays
Maximum voltage : 240 Vca
Maximum current : 1 A
Function : Programmable

Communication
- Modbus-RTU (with accessory: RS485-01; RS485-05; CAN/RS485-01; RS232-01 or RS232-05)
- Modbus/TCP (with accessory: MODBUSTCP-05)
- Profibus DP (with accessory: PROFDP-05)
- Profibus DPV1 (with accessory: PROFIBUS DP-01)
- Profinet (with accessory: PROFINETIO-05)
- CANopen (with accessory: CAN/RS485-01 or CAN-01)
- DeviceNet (with accessory: DEVICENET-05; CAN/RS485-01 or CAN-01)
- EtherNet/IP (with accessory: ETHERNET/IP-05 or ETHERNETIP-2P-05)
- EtherCAT (with accessory: ETHERCAT-01)
- BACnet (with accessory: RS485-01 or CAN/RS485-01)

Protections available
- Output overcurrent/short circuit
- Power supply phase loss
- Under/Overvoltage in power
- Overtemperature
- Motor overload
- IGBT's modules overload
- Fault/External alarm
- Breaking resistor overload
- CPU or memory failure
- Output phase-ground short circuit

Operation interface (HMI)
Avaliability : Included in the product
Installation : Local
Number of HMI buttons : 9

Operation interface (HMI)

Display : Graphic LCD
Indication accuracy : 5% of rated current
Speed resolution : 1 rpm
Standard HMI degree of protection : IP56
HMI battery type : CR2032
HMI battery life expectancy : 10 years
Remote HMI type : Detachable of the inverter
Remote HMI frame : Accessory
Remote HMI degree of protection : IP56

Ambient conditions

Enclosure : IP20
Degree of pollution : 2
Temperature
- Minimum : -10 °C / 14 °F
- Nominal [4] : 45 °C / 113 °F

Current reduction factor [5] : 2 % per °C of 45 (113) to 55 °C (131 °F)
Relative humidity (non-condensing)
- Minimum : 5%
- Maximum : 90%

Altitude
- Rated conditions : 1000 m (3281 ft)
- Maximum altitude allowed for operation : 4000 m (13123 ft)

Current Reduction factor[6]
- Current derating factor (for altitudes above rated) : 1% for each 100 m above
- Voltage derating factor (for altitudes above 2000 m / 6562 ft) : 1,1% for each 100 m above

Sustainability policies

RoHS : Yes
Conformal Coating : 3C2

Dimensions

Size : F
Height : 1234 mm / 48.6 in
Width : 430 mm / 16.9 in
Depth : 360 mm / 1.18 in
Weight : 132 kg / 291 lb

Mechanical installation

Mounting position : Surface or flange
Fixing screw : M10
Tightening torque : 37 N.m / 27.31 lb.ft
Allows side-by-side assembly : No
Minimum spacing around the inverter
- Top : 150 mm / 5.91 in
- Bottom : 250 mm / 9.84 in
- Front : 20 mm / 0.78 in
- Side : 80 mm / 3.15 in

Electrical connections

Cable gauges and tightening torque:

	Recommended cable gauge to 75 °C (167 °F)	Recommended tightening torque
Power	2x 70 mm² (2x 1/0 AWG) HD	Power 60,0 N.m (44,28 lb.ft) and braking 10,0 N.m (7,38 lb.ft)
Braking	Not applicable	Power 60,0 N.m (44,28 lb.ft) and braking 10,0 N.m (7,38 lb.ft)
Grounding	95,0 mm² (3/0 AWG)	10 N.m / 7.38 lb.ft
Control	0,5 to 1,5 mm² (20 to 14 AWG)	0,5 N.m / 0.37 lb.ft

Additional especifications

Maximum breaking current : Not available
Minimum resistance for the brake resistor : Not available
Recommended aR fuse : FNH2-630K-A
Recommended aR fuse : Not applicable
Recommended circuit breaker : To define
Recommended circuit breaker : Not applicable

Standards

Safety	- UL 508C - Power conversion equipment. - UL 840 - Insulation coordination including clearances and creepage distances for electrical equipment. - EN 61800-5-1 - Safety requirements electrical, thermal and energy. - EN 50178 - Electronic equipment for use in power instalations - EN 60204-1 - Safety of machinery. Electrical equipment of machines. Part 1: General requirements. Note: To have a machine in accordance with this

	standard, the machine manufacturer is responsible for installing an emergency stop device and supply disconnecting device. - EN 60146 (IEC 146) - Semiconductor converters. - EN 61800-2 - Adjustable speed electrical power drive systems - Part 2: General requirements - Rating especifications for low voltage adjustable frequency AC power drive systems.
Electromagnetic compatibility	EN 61800-3 - Adjustable speed electrical power drive systems - Part 3: EMC product standard including specific test methods. - EN 55011 - Limits and methods of measurement of radio disturbance characteristics of industrial, scientific and medical (ISM) radio-frequency equipment. - CISPR 11 - Industrial, scientific and medical (ISM) radio-frequency equipment - Eletromagnetic disturbance characteristics - Limits and methods of measurement. - EN 61000-4-2 - Eletromagnetic compatibility (EMC) - Part 4: Testing and measurement techniques - Section 2: Eletrostatic discharge immunity test. - EN 61000-4-3 - Eletromagnetic compatibility (EMC) - Part4: Testing and measurement techniques - Section 3: Radiated, radio-frequency, electromagnetic field immunity test. - EN 61000-4-4 - Eletromagnetic compatibility (EMC) - Part4: Testing and measurement techniques - Section 4: Electrical fast transient/burst immunity test. - EN 61000-4-5 - Eletromagnetic compatibility (EMC) - Part4: Testing and measurement techniques - Section 5: Surge immunity test. - EN 61000-4-6 - Eletromagnetic compatibility (EMC) - Part4: Testing and measurement techniques - Section 6: Immunity to conducted disturbances, induced by radio-frequency fields.
Mechanical construction	- EN 60529 - Degrees of protection provided by enclosures (IP code). - UL 50 - Enclosures for electrical equipment. - EN 60529 e UL 50

Certifications

Notes

1) Orientative motor power, valid for WEG Motors standard of IV poles. The correct sizing must be done according to the nominal current of the motor used, which must be less than or equal to the rated output current of the inverter;
2) Braking resistor is not included;
3) With category for emission level conducted;
4) Without derating and with minimum spaces;
5) For temperatures above the nominal and maximum temperature (with derating of current and minimum spaces);
6) For altitude over of specified;
7) All images are merely illustrative;
8) For more information, see the users manual of the CFW-11 (size F).