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Ecodesign for power drive systems, motor starters, power electronics & their driven applications

Part 2: Energy efficiency indicators for power drive systems and motor starters

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National foreword

This British Standard is the UK implementation of EN 50598-2:2014+A1:2016. It supersedes BS EN 50598-2:2014 which will be withdrawn on 17 November 2017.

The UK participation in its preparation was entrusted to Technical Committee PEL/22, Power electronics.

A list of organizations represented on this committee can be obtained on request to its secretary.

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English Version

Ecodesign for power drive systems, motor starters, power electronics & their driven applications - Part 2: Energy efficiency indicators for power drive systems and motor starters

Ecoconception des entraînements électriques de puissance, des démarreurs de moteur, de l'électronique de puissance et de leurs applications entraînées - Partie 2: Indicateurs d'efficacité énergétique pour les entraînements électriques de puissance (PDS) et les démarreurs de moteur

Ökodesign für Antriebssysteme, Motorstarter, Leistungselektronik und deren angetriebene Einrichtungen - Teil 2: Indikatoren für die Energieeffizienz von Antriebssystemen und Motorstartern

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Up-to-date lists and bibliographical references concerning such national standards may be obtained on application to the CEN-CENELEC Management Centre or to any CENELEC member.

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Comité Européen de Normalisation Electrotechnique
Europäisches Komitee für Elektrotechnische Normung

CEN-CENELEC Management Centre: Avenue Marnix 17, B-1000 Brussels

Foreword

This document (EN 50598-2:2014) has been prepared by CLC/TC 22X "Power electronics".

The following dates are fixed:

- latest date by which this document has to (dop) 2015-11-17
be implemented at national level by
publication of an identical national
standard or by endorsement
- latest date by which the national (dow) 2017-11-17
standards conflicting with this
document have to be withdrawn

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. CENELEC [and/or CEN] shall not be held responsible for identifying any or all such patent rights.

This document has been prepared under a mandate given to CENELEC by the European Commission and the European Free Trade Association.

EN 50598, *Ecodesign for power drive systems, motor starters, power electronics & their driven applications*, will consist of the following parts:

- *Part 1: General requirements for setting energy efficiency standards for power driven equipment using the extended product approach (EPA), and semi analytical model (SAM);*
- *Part 2: Energy efficiency indicators for power drive systems and motor starters;*
- *Part 3: Quantitative ecodesign approach through life cycle assessment including product category rules and the content of environmental declarations.*

The CLC/TC 22X/WG 06 is the enabled task force for dealing with the mandate M/476 from European Commission for the standardization in the field of variable speed drives and/or power drive system products.

It has been set a close collaboration with several other technical committees (i.e. CLC/TC 2; CLC/TC 17B) in order to provide a comprehensive standard for energy efficiency and ecodesign requirements together with a pilot stakeholder committee CEN/TC 197 from the customers side.

Key points:

- Clear requirements how to achieve an energy efficient driven equipment using a motor system;
- Requirements and limits for IE-classes for power electronic converters;
- Requirements and limits for IES-classes for power drive systems (PDS);
- Loss determination of the PDS and requirements for the link to the driven equipment in order to determine the energy efficiency classification/evaluation of the extended product;

- Requirements how to achieve the environmentally conscious design and environmental declaration of a motor system.

It is the intention of the working group that this document, once finalized as a European Standard series, will be further processed to an international consensus in IEC according to the UAP procedure agreement between CENELEC and IEC.

Foreword to amendment A1

This document (EN 50598-2:2014/A1:2016) has been prepared by CLC/TC 22X "Power electronics".

The following dates are fixed:

- latest date by which this document has to be implemented at national level by publication of an identical national standard or by endorsement (dop) 2017-06-28
- latest date by which the national standards conflicting with this document have to be withdrawn (dow) 2019-06-28

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. CENELEC [and/or CEN] shall not be held responsible for identifying any or all such patent rights.

This document has been prepared under a mandate given to CENELEC by the European Commission and the European Free Trade Association, and supports essential requirements of EU Directive(s).

For the relationship with EU Directive(s) see informative Annex ZZ, which is an integral part of this document.

Annex ZZ
(informative)

Relationship between this European Standard and the ecodesign requirements of Commission Regulation (EC) No 640/2009 aimed to be covered

This European standard has been prepared under a Commission's standardisation request, M/476 'Mandate to CEN, CENELEC and ETSI for Standardisation in the field of variable speed drives and/or Power Drive System products', to provide one voluntary means of conforming to ecodesign requirements of Commission Regulation (EC) No 640/2009 of 22 July 2009 implementing Directive 2005/32/EC of the European Parliament and of the Council with regard to ecodesign requirements for electric motors [OJ L 191/26].

Once this standard is cited in the Official Journal of the European Union under that Regulation, compliance with the normative clauses of this standard given in Table ZZ.1 confers, within the limits of the scope of this standard, a presumption of conformity with the corresponding ecodesign requirements of that Regulation, and associated EFTA Regulations.

Table ZZ.1 – Correspondence between this European Standard and Commission Regulation (EC) No 640/2009 of 22 July 2009 implementing Directive 2005/32/EC of the European Parliament and of the Council with regard to ecodesign requirements for electric motors [OJ L 191/26] and Commission's standardisation request M/476 'Mandate to CEN, CENELEC and ETSI for Standardisation in the field of variable speed drives and/or Power Drive System products'

Ecodesign requirements of Regulation (EC) No 640/2009 [OJ L 191/26]	Clause(s) / sub-clause(s) of this EN	Remarks / Notes
Article 3.2.: from 1 January 2015: motors with a rated output of 7,5-375 kW shall not be less efficient than the IE3 efficiency level, as defined in Annex I, point 1, or meet the IE2 efficiency level, as defined in Annex I, point 1, and be equipped with a variable speed drive. Article 3.3.: from 1 January 2017: motors with a rated output of 0,75-375 kW shall not be less efficient than the IE3 efficiency level, as defined in Annex I, point 1, or meet the IE2 efficiency level, as defined in Annex I, point 1, and be equipped with a variable speed drive.	Clause 4.1 and 4.2 set the definitions for the concept of reference losses and for the optional relevant "torque versus speed operating points (including part load conditions)". Clause 4.3 set the workflow requirements to analyse the variable speed drive in combination with driven equipment. The clauses 4.4. - 4.8 set the IE and the IES classification system for converters and variable speed drives. Clause 9 sets the requirements for determination and type testing to verify the efficiency classes.	The option to use an IE2 motor in a variable speed application instead of an IE3 motor depends mainly on the torque versus speed characteristic of the driven equipment and how it is applied. In order to do the right optional decision for maximum energy savings, EN 50598-2 gives the fundamental requirements, the workflows and the classification system for variable speed drives to do the fundamental assessment in the power range of 0,12 kW up to 1000 kW.

Annex I, point 2: Information on the mandatory requirement to equip motors, which do not meet the IE3 efficiency level with a variable speed drive, shall be visibly displayed on the rating plate, technical documentation of the motor	Clause 8 sets the requirements for the documentation that shall be provided by the manufacturers of the electronic frequency converters and the variable speed drives.	All energy efficiency related equipment labels (IE as well as IES classes) are addressed, in order to ensure a classification of the CDM, PDS. Also the provisions of sufficient information are fixed, to recognize this classification for the final application and/or system, where the converters or variable speed drives are used as components.
Annex I, point 2: Manufacturers shall provide information in the technical documentation on any specific precautions that must be taken when motors are assembled, installed, maintained or used with variable speed drives, including information on how to minimise electrical and magnetic fields from variable speed drives.	Clause 8.4 sets requirements for the determination of additional energy losses and part load conditions depending on the BDM/CDM/PDS architecture and the possible use of options for compliance to other performance or environmental requirements. Clause 2 sets the relevant information how to minimise electrical and magnetic fields from variable speed drives and the specific information by a reference to EN 61800-3 "Electromagnetic Compatibility Requirements and specific test methods". Annexes B 3.1 and B 3.2 describe the use of high frequency electromagnetic interference filters and low frequency line harmonics filters to minimise electrical and magnetic fields from variable speed drive systems.	Electromagnetic compatibility (EMC) requirements are specific items for variable speed drives and are provided by the dedicated product standard EN 61800-3. Following those requirements leads to a fully compliant operation of variable speed drives since decades.

WARNING 1: Presumption of conformity stays valid only as long as a reference to this European standard is maintained in the list published in the Official Journal of the European Union. Users of this standard should consult frequently the latest list published in the Official Journal of the European Union.

WARNING 2: Other Union legislation may be applicable to the motor systems falling within the scope of this standard.

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Introduction

The Technical Committee CLC/TC 22X has circulated on 2010-03-31 the document CLC/TC22X/Sec0100/DC including the mandate M/476 from the European Commission for standardization in the field of variable speed drives and/or power drive system products.

As the PDS contains converter driven motors, the requirements for measuring of the energy efficiency of motors with non-sinusoidal supply is under the responsibility of CLC/TC 2 covering the requirement from mandate M/470.

The document is based on the CENELEC technical board document referenced BT137/DG8058/INF also reproducing this EC-mandate.

The CLC/TC22X working group 6 as being the standardization task force for dealing with this Mandate has close collaboration with several other technical committees (i.e. CLC/TC2; CLC/TC17B).

Therefore CLC/TC 22X committee has been enabled responsible to clarify all relevant aspects in the field of energy efficiency and ecodesign requirements for power electronics, switchgear, control gear, and power drive systems and their industrial applications.

The sometimes controversial requirements are illustrated in Figure 1. The work has been agreed to provide the reasonable target as a best compromise.

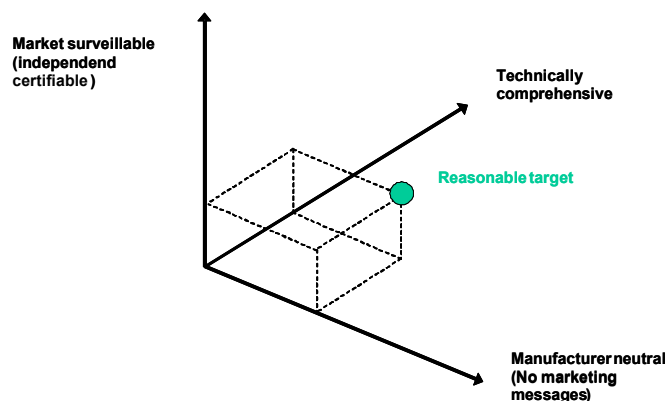


Figure 1 — Illustration of controversial requirements for the energy related product (ErP) standardization

EN 50598 is developed under the CENELEC projects number 24602 to 24604 for compliance with requirements from the horizontal mandate M/495.

Its three parts are together directly related to the mandates M/470 and M/476.

For the other mandates listed in Table 1, this standard could be applied if the future product standards developed will make reference to it.

Table 1 — Mandates of the European Commission given to CEN, CENELEC and ETSI and how they are contributed by these standard series parts

Mandates	Part 1	Part 2	Part 3
M/470 Motors		✓	✓
M/476 PDS		✓	✓
M/495 Horizontal all future Applications	✓	✓	✓
M/488 HVAC comfort fans	✓	✓	(✓)
M/498 Pumps	✓	✓	(✓)
M/500 Compressors	✓	✓	(✓)

In according with its Scope, this standard series does not deal with mechanical engineering components.

NOTE Geared motors (motor plus gearbox) needs to be treated for efficiency classes like a power drive system (converter plus motor). See EN 60034-30-1 for classification of the losses of a geared motor. The efficiency classes of gearboxes as individual components are under consideration.

1 Scope

This European Standard specifies the energy efficiency indicators for power electronics (e.g. complete drive modules, CDM), power drive systems and motor starters, all used for motor driven equipment in the power range of 0,12 kW up to 1 000 kW.

It specifies the methodology for determination of losses of the complete drive module (CDM), the power drive system (PDS) and the complete motor system.

It defines IE and IES-classes, their limit values and provides test procedures for the classification of the overall losses of the motor system.

Furthermore, this part of EN 50598 proposes a methodology for characterization of the best energy efficiency solution to be implemented. This depends on the motor driven system architecture, the speed/load profile and the operating points over time of the driven equipment.

The methodology of the extended product approach and the semianalytical models are defined in Part 1 of the series.

The structure of this EN 50598 contains the following:

- the losses of a standardized reference PDS (RPDS) and the mathematical model for their calculation are given and classified;
- the reference load/motor (RM) and the reference CDM (RCDM) are defined and can be used to determine the efficiency class of a motor system when one of its constituents is unknown;
- the requirements for determining the losses of a real PDS are given and are classified in comparison to the RPDS;
- the requirements for the type testing and the content of user documentation;
- some illustrations of losses in an overall system as an example are given in annexes;
- information about system and drive topologies are given in annexes.

Specific data for power losses of RCDM, RM, RPDS and IE/IES-classes are given for low voltages (100 V up and equal to 1 000 V), single axis AC/AC power drive systems with three phase induction motors. Geared motors need to be treated as standard motors.

All provided reference data is derived from PDS with induction motors, but valid for all types of PDS with other types of motors.

High voltage equipment does not need to be assessed in this edition of the document.

In EN 50598-3, the methodology for eco-design for environmental impact is defined.

NOTE The 50598 series does not cover energy efficiency classification of driven equipment, but provides input for the assessment of extended product approach.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

NOTE As it is intended by the working group to process this document, once finalized, as an IEC Standard, some normative references are given even in case if no European harmonized document exists.

EN 50347, *General purpose three-phase induction motors having standard dimensions and outputs — Frame numbers 56 to 315 and flange numbers 65 to 740*

EN 60034-1, *Rotating electrical machines — Part 1: Rating and performance (IEC 60034-1)*

EN 60034-2-1:2007, *Rotating electrical machines — Part 2-1: Standard methods for determining losses and efficiency from tests (excluding machines for traction vehicles) (IEC 60034-2-1:2007)*

EN 60034-6, *Rotating electrical machines — Part 6: Methods of cooling (IC Code) (IEC 60034-6)*

EN 60034-30-1, *Rotating electrical machines — Part 30-1: Efficiency classes of line operated AC motors (IE code) (IEC 60034-30-1)*

CLC/TS 60034-31, *Rotating electrical machines — Part 31: Selection of energy-efficient motors including variable speed applications — Application guide (IEC/TS 60034-31)*

EN 60947-4-1, *Low voltage switchgear and controlgear — Part 4-1: Contactors and motor starters — Electromechanical contactors and motor-starters (IEC 60947-4-1)*

EN 60947-4-2, *Low voltage switchgear and controlgear — Part 4-2: Contactors and motor starters — AC semiconductor motor controllers and starters (IEC 60947-4-2)*

EN 61800-5-1, *Adjustable speed electrical power drive systems — Part 5-1: Safety requirements — Electrical, thermal and energy (IEC 61800-5-1)*

IEC/TS 60034-2-3, *Rotating electrical machines — Part 2-3: Specific test methods for determining losses and efficiency of converter-fed AC induction motors*

IEC 60038:2009, *IEC standard voltages*

IEC 60050-161, *International Electrotechnical Vocabulary. Chapter 161: Electromagnetic compatibility*

IEC 60072-1, *Dimensions and output series for rotating electrical machines — Part 1: Frame numbers 56 to 400 and flange numbers 55 to 1080*

IEC/TS 62578, *Power electronics systems and equipment — Operation conditions and characteristics of active infeed converter applications*

3 Terms, definitions, symbols and abbreviations

3.1 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 60050-161 and the following apply.

3.1.1

Active Infeed Converter

AIC

self-commutated electronic power converters of all technologies, topologies, voltages and sizes which are connected between the a.c. power supply system (mains) and a stiff d.c.-side (current source or voltage source) and which can convert electric power in both directions (generative or regenerative) and which can control the reactive power or the power factor

Note 1 to entry: See IEC/TS 62578.

Note 2 to entry: In IEV these terms (VSC and CSC) are defined as voltage stiff a.c./d.c. converter [551-12-03] and current stiff a.c./d.c. converter [551-12-04]. Most of the AICs are bi-directional converters and have sources on the d.c. side. So they are known as voltage source converters and current source converters.

3.1.2 **Complete Drive Module (according to EN 61800-2)** **CDM**

drive module, consisting of the electronic power converter connected between the electric supply and a motor as well as extension such as protection devices, transformers and auxiliaries

Note 1 to entry: The AC/AC frequency converter which feeds the motor. Some countries use the term "Drive" instead of CDM. The term "Drive Controller" is also somehow used instead of CDM.

3.1.3 **crest factor**

ratio of the peak value and the RMS value of the waveform

3.1.4 **driven equipment**

equipment mechanically connected to the shaft of a motor

3.1.5 **Energy Efficiency Index** **EEl**

Energy Efficiency Index of an extended product (e.g. a pump unit) allowing to characterize its energy efficiency

Note 1 to entry: More specific definitions of the EEI may be specified by extended product committees.

3.1.6 **extended product** **EP**

combination of a motor system and a driven equipment

Note 1 to entry: See Figure 2.

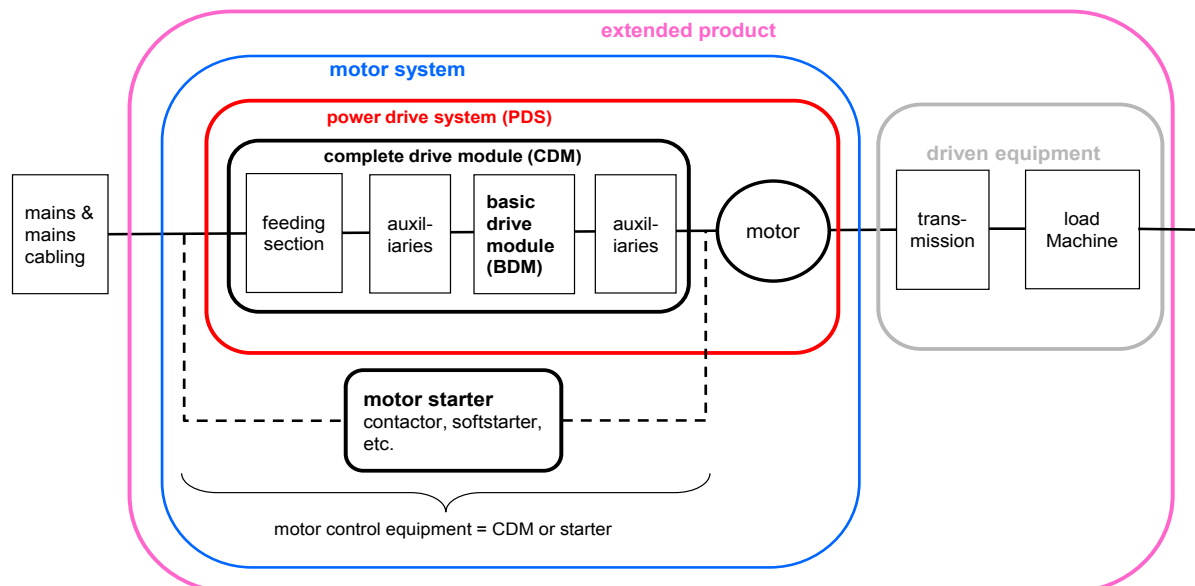


Figure 2 — Illustration of the extended product with included motor system

3.1.7

International Efficiency class

IE class

IE is an abbreviation for "International Efficiency" which stands for the efficiency classification of components of a motor system (3.1.9)

3.1.8

International Efficiency of Systems class

IES class

IES is an abbreviation for "International Efficiency of Systems" which stands for the efficiency classification of a motor system (e.g. PDS or a gear drive motor)

3.1.9

motor system

either a PDS or a motor connected to the mains by a motor starter according to EN 60947-4-1

3.1.10

Power Drive system (according to EN 61800-2)

PDS

system consisting of a CDM and a motor

3.1.11

pulse pattern

pattern of the switched voltages or currents, measurable at the terminal of the converter, resulting from pulse frequency and modulation schemes used

3.1.12

Reference Complete Drive Module

RCDM

complete drive module defined by mathematical equations and/or power losses, used as a basis for determining the IE class of an individual CDM

3.1.13

Reference Motor

RM

motor defined by mathematical equations and/or power losses, used as a basis for comparing other motors

3.1.14

Reference Power Drive System

RPDS

combination of the reference motor and the reference PDS

3.1.15

Single axis AC/AC CDM

CDM which feeds only one motor, in which case the axis refers to the mechanical output shaft of the motor

3.1.16

test load

artificial circuit that controls the output current I_{out} and output fundamental displacement factor $\cos\Phi$ of a CDM for testing or calculation purposes

Note 1 to entry: Test load may be a test motor or a different kind of load.

3.1.17

timefraction

percentage of time an application is operated at one specific load point i

3.1.18

torque-producing current

rotor current for an asynchronous motor

3.2 Symbols and abbreviations

For the purposes of this document, the following symbols and abbreviations apply.

3.2.1

c_{liquid}

specific heat capacity of liquid

3.2.2

E_D

switching loss energy per volt and per ampere of a power diode

3.2.3

E_T

switching loss energy per volt and per ampere of a power transistor

3.2.4

f_{sw}

The switching frequency is the number of switching events of one semiconductor within one second. It determines, together with the selected pulse pattern and the converter topology, the lowest frequency of non-controllable harmonics or interharmonics at the IPC (in-plant point of coupling) or the motor

3.2.5

$I_{\text{motor_cable}}$

Current in the motor cable of one power port (see EN 61800-2) of the PDS, used for calculating switching losses. $I_{\text{motor_cable}}$ represents a capacitive leakage current, which is normally for shielded motor cables

3.2.6

$I_{1,r\text{ CDM}}$

fundamental of the rated CDM or PDS input current waveform

3.2.7

I_r

rated CDM or PDS input current

3.2.8

I_{out}

output current

3.2.9

$I_{r,\text{out}}$

rated CDM output current

3.2.10

I_{rM}

rated motor current

3.2.11

$kI_{\text{DC_link}}$

load independent DC link loss parameter ($\frac{1}{\Omega \cdot A}$)

3.2.12

kI_{choke}

choke impedance, relative to the rated CDM impedance

3.2.13

$k2_{\text{DC_link}}$

load dependent DC link loss parameter ($\Omega \cdot A$)

3.2.14

$k2_{\text{choke}}$

relative voltage drop on the resistor part of the choke (/)

3.2.15

$P_{L,\text{cooling}}$

power losses generated by the cooling equipment of a CDM (e.g.fan losses), referred to the BDM (see EN 61800-2) losses if the CDM needs to be separately cooled

3.2.16

m

modulation index, relation of CDM output frequency to the nominal motor stator frequency

3.2.17

n_i

speed [rpm] at load point i

3.2.18

n_r

rated speed [rpm]

3.2.19

P_i

power consumption [kW] at load point i

3.2.20

$P_{\text{in,CDM}}$

input power of the CDM obtained from the power loss measurement

3.2.21

$P_{\text{in,PDS}}$

input power of the PDS obtained from the power loss measurement

3.2.22

P_{Lfe}

iron losses of a motor

Note 1 to entry: Compare EN 60034-2-1.

3.2.23

P_{Lfw}

friction and windage losses of a motor

Note 1 to entry: Compare EN 60034-2-1.

3.2.24

P_{LHL}

additional harmonic losses of a motor caused by non-sinusoidal power supply

Note 1 to entry: Compare IEC/TS 60034-2-3.

3.2.25

P_{LL}

additional load losses of a motor

Note 1 to entry: Compare EN 60034-2-1.

3.2.26

P_{LR}

rotor losses of a motor

Note 1 to entry: Compare EN 60034-2-1.

3.2.27

P_{LS}

stator winding losses of a motor

Note 1 to entry: Compare EN 60034-2-1.

3.2.28

P_{LTsin}

total losses of a motor at sinusoidal power supply

Note 1 to entry: According to EN 60034-2-1, Method 2-1-1B.

3.2.29

$P_{LT,Mot}$

total losses of a motor when supplied by a converter (non sinusoidal power supply)

Note 1 to entry: According to EN 60034-2-1, Method 2-1-1B.

3.2.30

$P_{out,CDM}$

output power of CDM obtained from the power loss measurement

3.2.31

$P_{out,PDS}$

output power of PDS obtained from the power loss measurement

3.2.32

P_r

rated Power of equipment which is assigned by its manufacturer

3.2.33

P_{proc}

power demand of the mechanical or fluidmechanical process

3.2.34

P_L

electrical power losses with the indices CDM refer to the complete drive module; Mot refers to the motor, PDS to the power drive system. Aux to the auxiliary devices like cables, transformers or filters

3.2.35

p_L

relative power losses are the per unit losses related to the nominal power of the device

3.2.36

$P_{L,CDM}$

power losses of a CDM

3.2.37

$P_{L,CDM, determined}$

power losses of CDM from the power loss determination method

3.2.38

$p_{L,CDM}$

relative power losses of the CDM, referred to its rated apparent power

3.2.39

$P_{L,choke}$

power losses in the choke section of a CDM

3.2.40

$P_{L,control}$

power losses in the control section of a CDM

3.2.41

P_{L,DC_link}

power losses of the DC link section of the CDM

3.2.42

$P_{L,inverter}$

power losses in the inverter section of a CDM

3.2.43

$P_{L,PDS, determined}$

power losses of PDS from the power loss determination method

3.2.44

$P_{L,rectifier}$

power losses in the rectifier section of a CDM

3.2.45

$P_{L,resistor}$

measured power losses of the resistor in comparative calorimetric measurement

3.2.46

$P_{L,on,D}$

on state power losses of a power diode

3.2.47

$P_{L,on,D, rectifier}$

on state power losses of a rectifier diode

3.2.48

$P_{L,on,T}$

on state losses of a power transistor

3.2.49

$P_{L,sw,D}$

switching power losses of a power diode

3.2.50

$P_{L,sw,T}$

switching power losses of a power transistor

3.2.51

$P_{r,M}$

rated power of a motor

Note 1 to entry: In the motor standard series EN 50034 this is named P_N .

3.2.52

$P_{L, stby}$

standby losses of a PDS

Note 1 to entry: Standby losses are generated when the PDS is powered up, but not providing current to the load. They are typically two to three orders of magnitude lower than the losses during operation. Their influence on the overall losses strongly

depends on the duty profile of the extended product. Besides this, they also depend on the requirements of the extended product in terms of wake-up time and communication.

3.2.53

Q

flow rate of a pump unit

3.2.54

Q_{BEP}

flow rate of the pump at the best efficiency point

3.2.55

Q_{cooler}

volumetric flow rate of the cooler in the calorimeter

3.2.56

r_{HL}

ration of additional harmonic losses when a motor is operated with a CDM compared to the losses at sinusoidal supply of a motor

3.2.57

$S_{\text{r, equ}}$

rated apparent power of a piece of equipment

3.2.58

$S_{\text{r, RCDM}}$

rated apparent power of the reference CDM

3.2.59

T

torque of a motor

3.2.60

t_{w}

working time of an equipment

3.2.61

T_{i}

torque [Nm] at operating point i

3.2.62

$U_{1, \text{r, out}}$

fundamental rated line to line CDM output voltage which is assumed, for the reference CDM, to be 400 V, if not stated differently

3.2.63

U_{DC}

DC link voltage of a CDM

3.2.64

$U_{\text{D, r}}$

on state voltage of a power diode at rated CDM current

3.2.65

$U_{\text{D, r, rectifier}}$

on state voltage of a rectifier diode at rated CDM current

3.2.66

$U_{\text{D, th}}$

threshold voltage of a power diode

3.2.67

$U_{D,th,rectifier}$

threshold voltage of a rectifier diode

3.2.68

U_{mL1}

line to neutral voltage of the power supply system in phase L1

3.2.69

$U_{T,r}$

on state voltage of a power transistor at rated CDM current

3.2.70

$U_{T,th}$

threshold voltage of a power transistor

3.2.71

W_w

electrical energy demand of extended product during working time

3.2.72

λ

power factor of an equipment input current and voltage: $\lambda = P_{equ}/S_{r,equ}$

3.2.73

$\Delta p_{L,CDM}$

uncertainty [%] of power loss determination method for CDM

3.2.74

$\Delta P_{L,CDM}$

uncertainty [W] of power loss determination method for CDM

3.2.75

$\Delta p_{L,PDS}$

uncertainty [%] of power loss determination method for PDS

3.2.76

$\Delta P_{L,PDS}$

uncertainty [W] of power loss determination method for PDS

3.2.77

θ_{in}

input temperature of cooling medium (air, liquid) in calorimetric measurement

3.2.78

θ_{inside}

temperature of cooling air between two calorimetric measurement chambers

3.2.79

θ_{out}

output temperature of cooling medium (air, liquid) in calorimetric measurement

3.2.80

φ

phase angle between the fundamental CDM input voltage and the fundamental CDM input current

3.2.81

ϕ

phase angle between the fundamental CDM output voltage and the fundamental CDM output current

3.2.82

ϕ_r

phase angle between the fundamental CDM output voltage and the fundamental CDM output current at rated torque and speed

4 Concept of the reference PDS (RPDS), the reference CDM (RCDM) and the reference motor (RM)

4.1 General

In order to determine the most efficient extended product for a given application, it is necessary to be able to easily compare several drive topologies and/or several control strategies. The Extended Product Approach described in EN 50598-1 allows to do that.

To support this in an appropriate and standardized way, the concept of the so called "Reference PDS (RPDS)" is introduced. The standardized RPDS, consisting of a reference CDM (RCDM) and a reference converter fed motor (RM) allows the comparison of the energy consumption of an average technology PDS.

That definition of the RPDS is generic and is independent from a specific product or manufacturer. It allows:

- to set limit values for the classifications;
- to classify a real PDS against the RPDS;
- to classify the CDM and apply the future IEC/TS 60034-30-2 classification for converter fed motors.
- to limit the the assessment to only a few appropriate measurement points or calculation results, to develop the energy consumption of different driven applications

Examples for relevant input values for the classification of different driven applications:

Pump units or other so called "square torque loads" will typically require the relative losses or the input powers P_1 of the points $p_{L, PDS (50; 25)}$, $p_{L, PDS (100; 50)}$ and $p_{L, PDS (100; 100)}$ in order to calculate the losses of the embedded Motor system. The permissible loss tolerances is $\pm 10 \%$ of the losses in each operating point.

Hoisting equipment or other so called "constant torque loads" will additionally need the points $p_{L, PDS (0; 25)}$, $p_{L, PDS (0; 50)}$ and $p_{L, PDS (0; 100)}$ in order to determine the losses of the embedded motor system.

The losses of the reference power drive system shall be used as well for the evaluation of equipment with a rated voltage other than 400V and other than 4-pole motors.

4.2 Predefinition of the speed versus torque loss points of a RPDS, a RCDM, a RM and the associated power losses

All driven equipment can be described by the drive power required by the physics of the machine/application. The power requirements are the product of torque and speed at any working points. At each operating point there is an associated power loss in the motor system.

The collection of (torque, speed) operating points at which the motor system may potentially be operated is infinite. Theoretically, it is necessary to know the amount of power losses generated at each point. In practice however, it is sufficient to know the power losses at a limited number of specific points (eight) which are specified for the RPDS in Figure 3, for the RM in Figure 3 and for the RCDM in Figure 3.

For operating points with speeds greater than zero, the losses are usually given as a percentage of the mechanical output power. In other approaches the rated efficiencies (η) are defined as the ratio in percent of the rated mechanical output power to the required electrical input power (including losses).

In this standard the power losses related to the nominal power of the power drive system (p in %) are considered instead of efficiency. This shall be done in order to secure the generality of the extended product approach.

Driven equipment, for which a standstill torque is required, exists. For such equipment the efficiency is not an appropriate value to be used in the extended product approach.

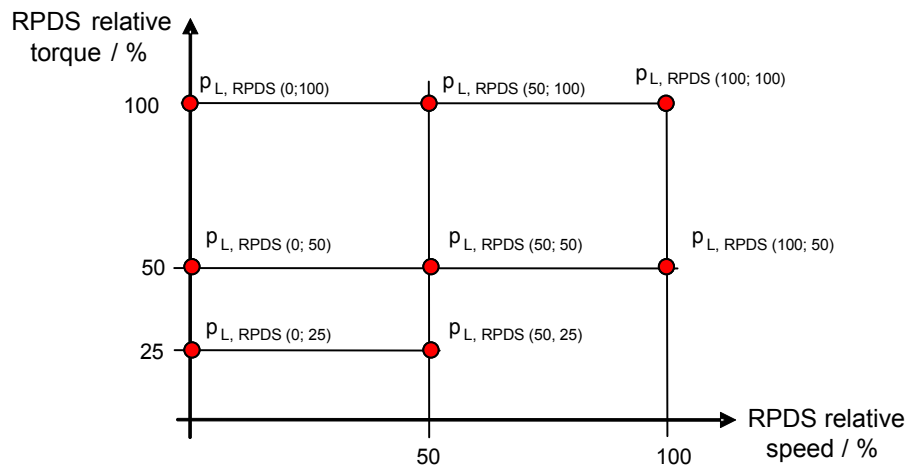


Figure 3 — Illustration of the operating points for speed versus torque to determine the relative power losses of the power drive system (RPDS)

As defined, the absolute losses of the RPDS shall be the sum of the RCDM losses plus the RM losses. Therefore those losses shall be calculated point by point at the loss points in Figure 4 and Figure 5 by the following formula:

$$P_{L,RPDS} = P_{L,RM} + P_{L,RCDM} \quad (1)$$

The relative losses of the RPDS are calculated from the relative losses of the RCDM and the RM as follows:

$$p_{L,RPDS} = \frac{p_{L,RM} \cdot P_{r,RM} + p_{L,RCDM} \cdot S_{r,RCDM}}{P_{r,RM}} \quad (2)$$

At rated speed and torque, a modified formula according to Formula (28) has to be used.

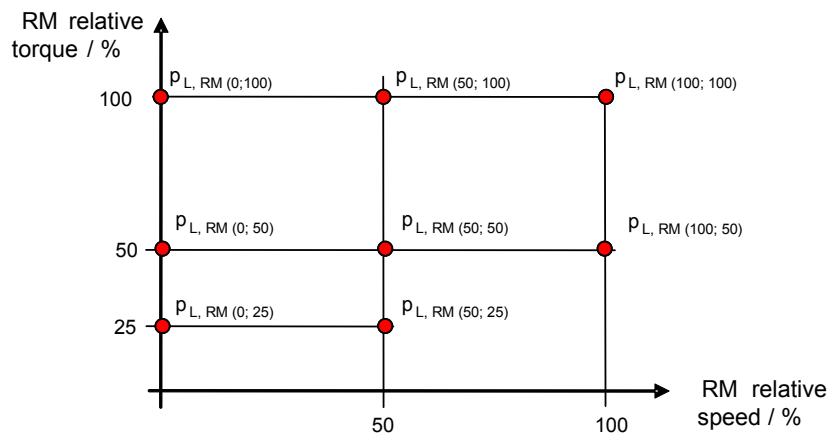


Figure 4 — Illustration of the operating points for speed versus torque to determine the relative power losses of the reference motor (RM)

The loss points of the reference CDM (RCDM) cannot be given as a percentage of speed, torque of corresponding rated values because the CDM provides only currents and voltages at the output. Moreover, the output voltage shall be limited to 90 % to avoid overmodulation techniques for fair comparison.

NOTE 1 The RCDM losses at 90 % output voltage are very similar to the RCDM losses at 100 % output voltage (inverter losses are slightly higher, whereas rectifier losses are slightly lower) and can consequently be used to calculate the RCDM losses at 100 % speed.

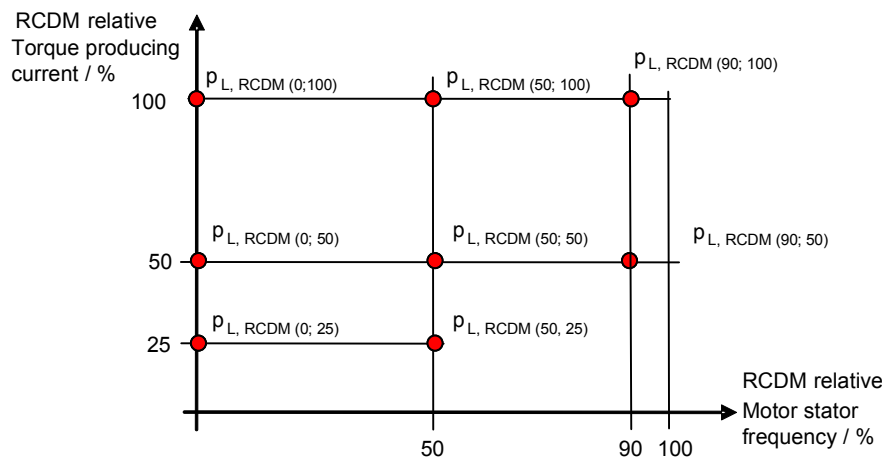


Figure 5 — Illustration of the operating points of the RCDM depending on the relative torque-producing current and the relative motor stator frequency, to determine the losses of reference complete drive module (RCDM)

NOTE 2 For an asynchronous motor, the torque-producing current is the rotor current.

NOTE 3 For physical reasons the illustrated load points on the y-axis of Figure 5 $p_{L, RCDM}(0, n)$ will require a fraction of the output voltage greater than zero in order to let current flow through the resistance of the motor windings.

The relative fundamental CDM output voltage shall be no lower than the relative CDM output frequency.

The losses for intermediate operating points, if necessary, can be determined according to one of the calculation models presented in G.2.1:

- a) maximum losses in neighbouring predefined loss points;
- b) two-dimensional linear interpolation between neighbouring loss points;
- c) loss calculation according to the mathematical model described in 5.1.

When testing a deviation of the relative rotor speed from the defined operating points in Figure 3 up to the rated slip shall be allowed. At 0 Hz, a deviation of up to 5 Hz of the rated frequency shall be allowed.

4.3 Combining the PDS losses with the driven equipment

4.3.1 Workflow for the semi-analytical model (SAM)

The determination model for the losses or the energy efficiency index of an extended product is called "semi analytical model (SAM)", which includes physical and mathematical parameters and calculation algorithms of the subparts of an EP.

The workflow and responsibilities for determining the efficiency classification of an extended product is shown in Figure 6.

It also illustrates how the SAM of the motor system (left hand side) shall be linked to the SAM of the driven equipment (right hand side). The link in between both semi analytical models shall be the load loss points of the PDS and their permissible tolerances. The actual needed operating points shall be required by the semi analytical model of the driven equipment.

The PDS data containing the PDS losses according to Figure 3 (left hand side of Figure 6) is defined in this standard, whereas the semi analytical energy consumption models of the PDS-driven application (right hand side of Figure 6) shall be drafted by their responsible product committees by using the same approach. An example for PDS driven pump units is given in 4.3.2. Figure 7 shows how the different data sources shall be combined.

It is the responsibility of the technical committees for specific applications to standardize publicly available SAM's for their applications.

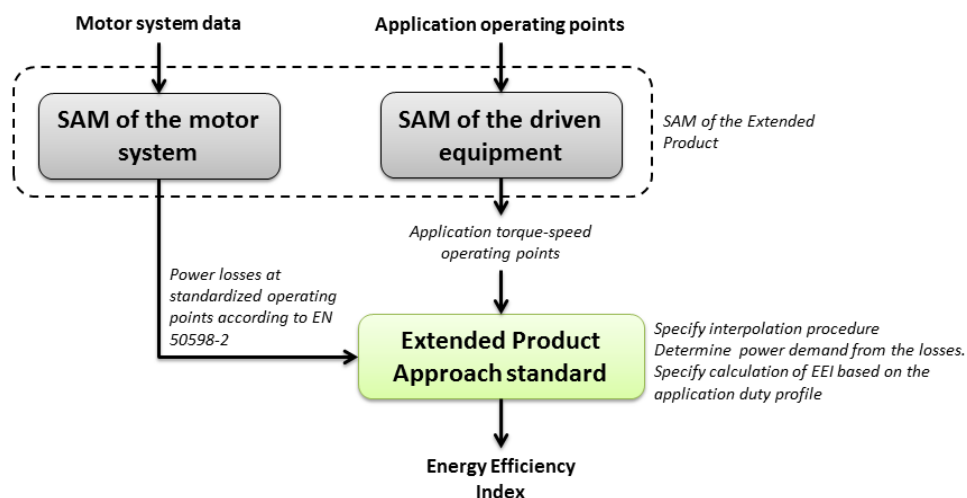


Figure 6 — Illustration of the workflow to determine the energy efficiency index (EEI) of an extended product

This standard specifies how to determine the power losses of the motor system.

The extended product committee shall specify the tolerances that shall apply to this process.

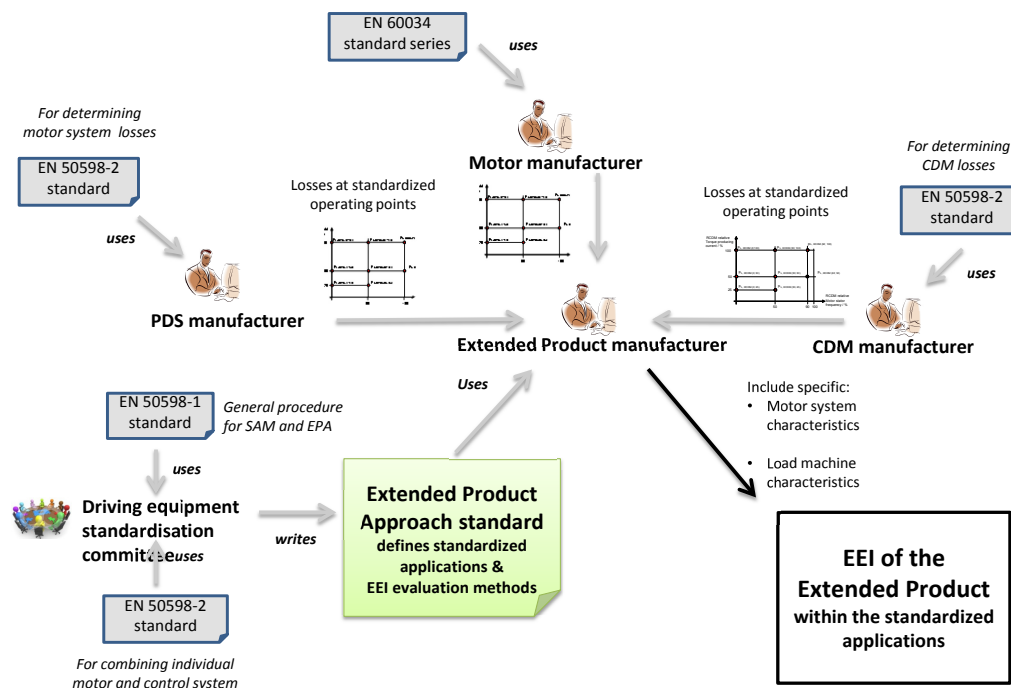


Figure 7 — Illustration how to combine different data sources to determine the energy efficiency index (EEI) of an extended product

4.3.2 Example for required operating points in order to determine the losses for a pump system

Pumps and other flow rate machines will usually have a torque requirement proportional to the square of the speed.

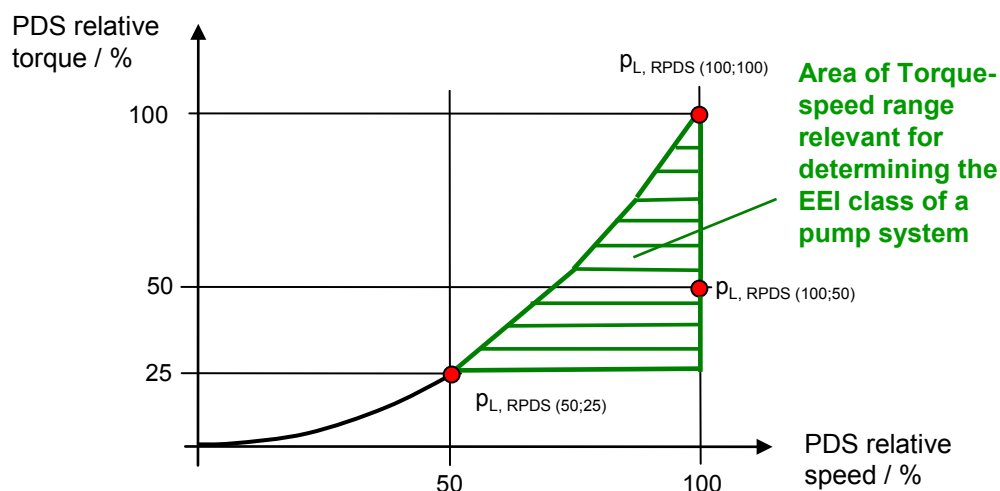


Figure 8 — Three points of relative losses and shaded area of interest for the pump manufactures while defining the EEI (Energy Efficiency Index) of a pump unit

Providing the electrical power losses of the three points $P_{L,PDS(50; 25)}$, $P_{L,PDS(100; 50)}$ and $P_{L,PDS(100; 100)}$ enables the pump manufacturers to derive the power input of the extended pump product inside the shaded area.

A limited number of operation points is sufficient in this case because other operating points shall be calculated by interpolation (see G.2.1).

NOTE 1 The loss value description within the shaded area is appropriately to be given with a permissible tolerance of $\pm 10\%$ as this tolerance will not significantly affect the EEI value of the pump unit. On the other hand this tolerance allows standardizing and classifying the RPDS for that purpose.

The electrical power losses of the PDS at the 50 % speed versus 25 % torque point is the calculated sum of the power losses of all its components including the feeding transformer, if it is dedicated to feed only this PDS and all its auxiliary components such as filters or cables.

$$P_{L,PDS(50,25)} = P_{L,CDM(50,25)} + P_{L,Aux(50,25)} + P_{L,Mot(50,25)} \quad (3)$$

$(P_{L,CDM} + P_{L,Aux})$ results in the power losses of a reference complete drive module together with auxiliaries, like filtering or AICs (as an alternative rectifier type), with an agreed permissible tolerance of $\pm 10\%$. It requires the most influencing service parameters for the losses.

NOTE 2 The „Reference CDM (RCDM)“ might not be an available product on the market, it might be a general available product from all concerned manufacturers.

$P_{L,Mot}$ describes the losses of a converter fed „reference motor“ following the determination methods according to IEC/TS 60034-2-3 including additional harmonic frequency losses at $f_{sw}=4\text{kHz}$ (rated power up to 90 kW) or $f_{sw}=2\text{kHz}$ (rated powers above 90 kW).

$$P_{L,Mot} = P_{\text{Fundamental}}(T, f_{sw}) + P_{\text{Harmonic}}(n, T, f_{sw})$$

NOTE 3 The „Reference Motor (RM)“ might not be an available product on the market, it might be a general available product from all concerned manufacturers. It may be as simple as any motor which has the required voltage rating and with an output power rating equal to or the next preferred rating above that of the converter. An electronic load is a possibility to simplify testing.

4.4 IE Classes of a line fed motor (IE1 up to IE9)

According to EN 60034-30-1, the IE classes for the device "line fed motor" is defined as IE1 up to IE4 (or IE5 respectively). The range IE5 up to IE9 is currently not used and under consideration.

It is assumed that the nine classes IE1 to IE9 will be sufficient to cover future efficiency classes of line-fed motors.

4.5 IE Classes of a converter fed motor (IE1 up to IE9)

In accordance of IEC/TS 60034-2-3 the harmonic losses contribute to higher relative losses (about 15 % to 25 %) in the motor.

If the motor is not designed to be supplied from the mains, its total losses at nominal power shall be indicated as an IE class.

The IE classes for the converter driven motors are under consideration in IEC/TC 2.

4.6 IE Classes of a converter (complete drive module, CDM) (IE0 up to IE9)

The reference CDM (RCDM) shall be declared with the efficiency class "IE1".

To declare the efficiency class of the CDM without considering the whole resulting PDS and to reflect the technological impact of the most significant parameter, the so called "Test load" shall be used as a defined unit.

The operating point for the IE class determination shall be taken according to Clause 7.

AIC according to IEC/TS 62578, which are CDM with the ability to feedback braking energy from inertia of the load back to the electric power supply system, can be excluded from the IE classification. The relative losses of such AIC are typically twice the losses of a CDM with no feedback option. Therefore the huge efficiency contribution of an AIC cannot be demonstrated by just displaying its IE class and might be an option of the extended product with an embedded AIC.

CDMs having mains current THD of 10 % or lower (according to IEEE 519), e.g. active rectifier fed CDMs, can be excluded from the IE classification. The relative losses of active rectifier are typically twice the losses of a CDM with diode rectifier. However, the efficiency contribution of an active rectifier can be seen in better power grid utilization and lower system level losses and disturbances (power transformer, cabling, voltage harmonics, flicker).

4.7 IES Classes of a PDS (IES0 up to IES9)

The classification of the PDS shall be declared in a range of IES0 up to IES2. IES classes remain limited to IES0, 1 and 2 for this first edition of the document.

The limit values for the classes IES3 to IES9 are subject to future editions.

The relative losses of a PDS shall be determined by calculation or measurement. The calculation shall be done by arithmetic summation of the absolute losses of the converter fed motor plus the converter and the auxiliaries.

The so called "Reference PDS (RPDS)", see Figure 3, shall be classified as class IES1.

4.8 Consistency of IE, IES classes

Consistency of the IE classes in this context does not mean that one could sum up an IE1 Motor plus an IE2 CDM to achieve PDS of the class IES3.

The individual IE classes are necessary to independently classify a converter fed motor or just a CDM or just a motor without knowing the final motor system.

Generally the IE classes will show increased efficiency or decreased relative power losses with increasing ordinal number.



Line fed motors Efficiency	Converter fed motors Efficiency	Converters (CDM) losses related to rated power	Power Drive systems (PDS) losses related to rated power
IE0 – not used	IE0 – u.c.	IE0 – more than 25% higher than reference value	IES0 – more than 20% higher than reference value
IE1 – can be mostly technically achieved	IE1 – u.c.	IE1 - reference value $\pm 25\%$	IES1 - reference value $\pm 20\%$
IE2 – can be achieved by enhancement	IE2 – u.c.	IE2 – more than 25% lower than reference value	IES2 – more than 20% lower than reference value
IE3 – needs significant amount of techniques	IE3 – u.c.	IE3 – u.c.	IES3 – u.c.
IE4 – will require new techniques	IE4 – u.c.	IE4 – u.c.	IES4 – u.c.
IE5 – experimental new technologies	IE5 – u.c.	IE5 – u.c.	IES5 – u.c.
IE6 – not used	IE6 – u.c.	IE6 – u.c.	IES6 – u.c.
IE7 – not used	IE7 – u.c.	IE7 – u.c.	IES7 – u.c.
IE8 – not used	IE8 – u.c.	IE8 – u.c.	IES8 – u.c.
IE9 – not used	IE9 – u.c.	IE9 – u.c.	IES9 – u.c.

u.c. = under consideration

NOTE IE classes for line fed motors are defined in EN 60034-30-1.
IE classes for converter fed motors will be defined in the future IEC/TS 60034-30-2 (in preparation).

Figure 9 — Metrical relation of IE, IES classes

4.9 Determination of the IES class of a resulting PDS by application of "reference" and "test" devices and guidance for the manufacturers

A motor manufacturer may determine the losses of his motor and define an IE class according to Figure 9. He may also define an IES class for a PDS using his motor. For this he shall determine the relative losses for his motor together with a RCDM.

A CDM manufacturer shall declare the losses of his dedicated CDM and display an IE class according to Figure 9 and may also declare an IES class for a PDS equipped with his CDM. For this, he shall measure or calculate the losses for his CDM and add in case real motor data are not available the losses of the RM.

The CDM manufactures provide information in the documentation, according to the determination methods described in Clause 9, about expected IES classes for different combinations of a CDM and selected specific motors using the methods of this standard. For this expected IES class of a specific CDM and a specific motor, the efficiency shall be allowed to be increased using the control features of the CDM.

The spreadsheet on how to use the "test" or "reference" devices for determination of the IE performances or determination of the IES class of a resulting PDS is shown in Figure 10. Also the guidance for just CDM or just Motor manufacturers is given to determine the IES class of a resulting PDS together with the "test" or "reference" devices.

For PDS manufacturers the upper left handed intersection field of "Motor" and "CDM" is applicable.

Combination of	CDM	Test CDM	Reference CDM (RCDM)	
Motor	determine the IES class of the resulting PDS	determine the IE performance of the given motor (IEC TS 60034-2-3)	determine the IES Class of the resulting PDS	Guidance for motor manufacturer
Test Load	determine the IE performance of the given CDM	combination not used	combination not used	
Reference Motor (RM)	determine the IES Class of the resulting PDS	combination not used	calculation model of a reference PDS	
	Guidance for CDM manufacturer			

Figure 10 — Guidance for CDM and Motor manufacturers for the usage of "test" and "reference" devices to determine the IE-/IES classes

Following this approach the IES efficiency class of a final PDS can be determined in advance even if only one component (the motor or the CDM) is available.

5 Mathematical model of the CDM, motor and PDS

5.1 General

The mathematical model given in this clause describes the procedure to calculate the losses of the addressed CDM, motor and PDS. It consequently allows determining the losses of a product without measurements. The model consists of formulae, variables and parameters. The formulae describe the state of the art loss calculation procedure, which is generally accepted today and which is published in literature. The variables depend on the operating point of the evaluated CDM, motor or PDS. The parameters are physical values describing a real product. In order to determine the losses of a product, these parameters have to be set according to specific design of the product. For the reference CDM(RCDM), reference motor (RM) and reference PDS (RPDS), reference parameters are defined in each section.

The procedure of the loss determination is illustrated in Annex J.

5.2 CDM

5.2.1 General procedure and definition of the CDM and the test load

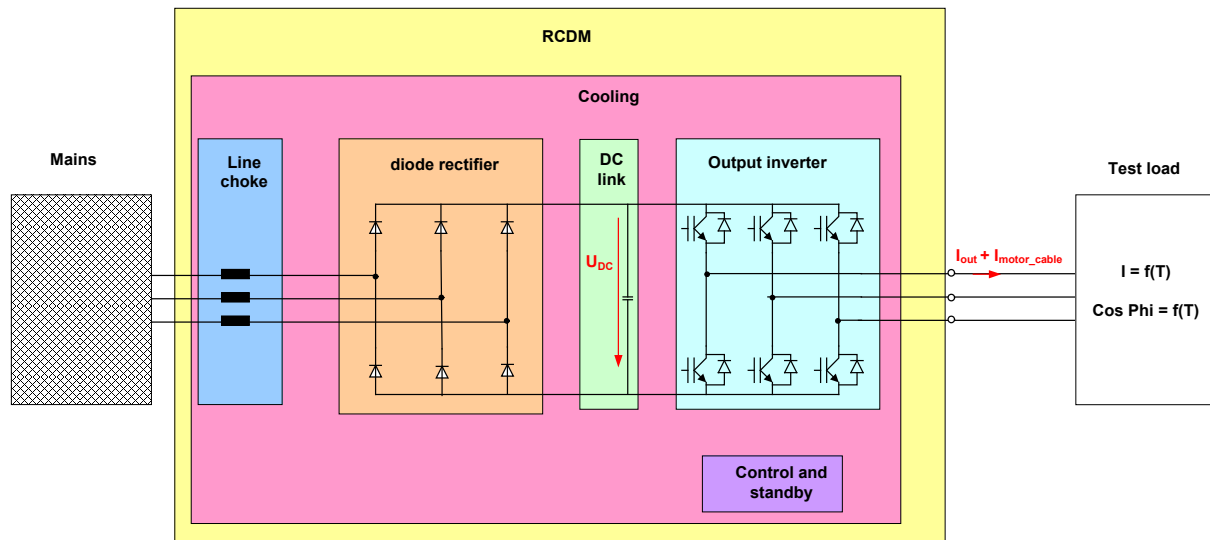


Figure 11 — Illustration of the CDM and the test load

Basically, it is the goal to describe the CDM losses as a function of torque and speed of the PDS. However, the CDM losses depend on its relative output voltage, which is no lower than the relative output frequency, and the output current of the inverter as well as on the phase angle between fundamental inverter output voltage and fundamental inverter output current. In the first step, the motor speed has to be transferred into an inverter output frequency, and the motor torque has to be converted to an inverter output current and a phase angle between fundamental output current and output voltage of the CDM.

In a first order approximation, the relative output speed of the PDS can be regarded as identical to the relative inverter output frequency. This is at least true in the operating field up to the nominal motor speed. In the range of field weakening, the relative inverter output voltage remains 1.00 for all motor speeds above the nominal motor speed.

The transfer function of motor torque into inverter output current and a phase angle between the fundamental inverter output voltage and the fundamental inverter output current depends on the motor which is connected to the PDS. In order to give a reproducible basis for a CDM evaluation, values for a test load are given. These values depend on the rated power. For standard 4 pole IE2 400V 50Hz and 60Hz asynchronous motors of all voltage classes from 100Vac to 1 000Vac, the following data obtained by measurements on real motors shall be used as a test load data:

Table 2 — Minimum test load currents at different points of operation

torque producing current /%	Test load current $\frac{I_{out}}{I_{r,out}}$ / % for the apparent power range $S_{r,eq}$ of				
	0,278kVA (0,12kW) to <1,29kVA (0,75kW)	1,29kVA (0,75kW) to <7,94kVA (5,5kW)	7,94kVA (5,5kW) to <56,9kVA (45kW)	56,9kVA (45kW) to <245kVA (200kW)	245kVA (200kW) to <1209kVA (1000kW)
25	0,79	0,58	0,45	0,42	0,39
50	0,81	0,71	0,60	0,58	0,56
75	0,89	0,82	0,79	0,78	0,77
100	1,00	1,00	1,00	1,00	1,00

Table 3 — Test load displacement factor between fundamental output current and fundamental output voltage at different points of operation

torque producing current /%	Test load displacement factor $\cos \phi$ for the apparent power range $S_{r,eq}$ of				
	0,278kVA (0,12kW) to <1,29kVA (0,75kW)	1,29kVA (0,75kW) to <7,94kVA (5,5kW)	7,94kVA (5,5kW) to <56,9kVA (45kW)	56,9kVA (45kW) to <245kVA (200kW)	245kVA (200kW) to <1209kVA (1000kW)
25	0,34	0,38	0,49	0,54	0,57
50	0,51	0,60	0,71	0,75	0,78
75	0,64	0,72	0,80	0,83	0,85
100	0,73	0,79	0,85	0,86	0,87

Test load current in Table 2 and test load phase angle in Table 3 for different related torque values depend on the rated power. In order to limit the amount of required data, motors in a certain power range are classified within one class. The amount of uncertainty on the resulting power losses of the CDM introduced thereby is small enough to justify the simplification. Permissible tolerances when testing are defined in 9.9. The test load data in Table 2 and Table 3 can be used for any CDM relative output frequency. Data for torque producing currents different from the defined operating points in Table 2 and Table 3 shall be obtained by linear inter- and extrapolation from the defined values.

The mathematical model of a CDM shall be calculated with its rated output current. If a CDM is not specified with a rated output current, but only with a rated real power $P_{r,M}$, its rated CDM output current

shall be calculated from the rated real power by the following formula, using the phase angle from Table 3 and the IE2 50Hz efficiency η_{nMotor} defined in IEC 60034-30:

$$I_{r,out} = \frac{P_{r,M}}{\sqrt{3} \cdot U_{1,r,out} \cdot \cos \Phi \cdot \eta_{nMotor}} \quad (4)$$

The rated apparent CDM output power shall be calculated as follows:

$$S_{r,eqv} = \sqrt{3} \cdot U_{1,r,out} \cdot I_{r,out} = \frac{P_{r,M}}{\cos \Phi \cdot \eta_{nMotor}} \quad (5)$$

For calculating the losses of a CDM with the input variables from Table 2 and Table 3, the analytical Formulae (6) to (17) given below shall be used. In order to calculate the losses of a real CDM, the parameter values of the real CDM shall be used.

The results of the RCDM calculations are given in Table 20 for the IE class determination and in Table A.1 for the eight operating points defined in Figure 5. The RCDM is based on 400 V supply voltage.

In contrast to Annex B, which describes the PDS sub-frames from the mains to the load, the following section starts with those parts of the PDS creating highest losses, followed by the other parts contributing to the overall PDS losses with a minor impact.

5.2.2 Output inverter losses

5.2.2.1 General

The major part of the CDM losses is created by the output inverter section of the CDM. Its losses are described by the following analytical formulae, which are well established in literature. These formulae assume that the CDM output current is sinusoidal and the PWM pulses are randomly distributed over the sinusoidal current fundamental waveform. The random distribution is achieved as soon as the PWM frequency is at least 20 times the fundamental frequency of the motor current and the standard space vector modulation algorithm is used. Reduced losses due to overmodulation of the CDM are not taken into account. The reference CDM is consequently calculated according to these assumptions. For the loss calculation of a real CDM, the parameter values on power semiconductors shall be determined either at actual temperature when operating the CDM or at maximum operating temperature specified in the datasheet.

5.2.2.2 Transistor on state losses

Transistor on state losses shall be calculated according to the following formula:

$$P_{L,on,T} = \sqrt{2} \cdot I_{out} \cdot U_{T,th} \cdot \left(\left(\frac{1}{2\pi} \right) + \frac{1,22 \cdot m \cdot \cos \phi}{8} \right) + \frac{U_{T,r} - U_{T,th}}{I_{r,out}} \cdot 2 \cdot I_{out}^2 \cdot \left(\frac{1}{8} + \frac{1,22 \cdot m \cdot \cos \phi}{3\pi} \right) \quad (6)$$

The RCDM parameters in Formula (6) are:

Table 4 — Reference parameters for Formula (6)

Abbreviation	Description	RCDM parameter value	Unit
$U_{T,th}$	Threshold voltage of the power transistor (IGBT)	1,0	V
$U_{T,r}$	On state voltage of the power transistor (IGBT) at rated CDM output current	2,3	V
$I_{r,out}$	rated CDM output current, rms value		A

The variables in Formula (6) are:

Table 5 — Variables for Formula (6)

Abbreviation	Description	Unit
I_{out}	CDM output current, rms value according to Table 2	A
ϕ	phase angle between fundamental CDM output voltage and fundamental CDM output current according to Table 3	°
m	modulation index, identical to the relative CDM output frequency	

5.2.2.3 Free wheeling diode on state losses

Diode on state losses shall be calculated according to the following formula:

$$P_{L,on,D} = \sqrt{2} \cdot I_{out} \cdot U_{D,th} \cdot \left(\left(\frac{1}{2\pi} \right) - \frac{1,22 \cdot m \cdot \cos \phi}{8} \right) + \frac{U_{D,r} - U_{D,th}}{I_{r,out}} \cdot 2 \cdot I_{out}^2 \cdot \left(\frac{1}{8} - \frac{1,22 \cdot m \cdot \cos \phi}{3\pi} \right) \quad (7)$$

The RCDM parameters in Formula (7) are:

Table 6 — Reference parameters for Formula (7)

Abbreviation	Description	RCDM parameter value	Unit
$U_{D,th}$	Threshold voltage of the power diode	1,1	V
$U_{D,r}$	On state voltage of the power diode at rated CDM output current	2,4	V

The variables in Formula (7) are identical to the variables in Formula (6).

5.2.2.4 Transistor switching losses

It is standard practice in power IGBT datasheets to describe the transistor switching energy as a function of the inverter output current. Usually, this value is obtained by recording the IGBT collector to emitter voltage and the IGBT collector current during switching, multiplying those graphs to obtain the instantaneous power losses and integrating those losses over one switching event to finally get the switching loss energy. In a first order approximation, the resulting curve shows the energy increasing in a linear way with the collector current and the DC link voltage of the inverter. The ratio between the switching energy and the product of DC link voltage and IGBT collector current is often described in literature as a factor E_T . This factor contains the sum of the loss energy at switching on and switching off of a power transistor.

At low current, the current which is relevant for determining the switching losses is higher than the inverter output current, because the motor cables lead to an additional output current. In order to consider this effect, a correction term I_{motor_cable} is introduced. This current is added to the inverter output current for the calculation of the switching losses. For the reference converter, a simple model for the cable current is given in Table 7 below.

Assuming the inverter is producing a sinusoidal output current with a fundamental frequency that is substantially (at least factor 15) lower than the switching frequency, the transistor switching losses shall be calculated according to the following formula:

$$P_{L,sw,T} = \frac{E_T}{\pi} \cdot U_{DC} \cdot \sqrt{2} \cdot (I_{out} + I_{motor_cable}) \cdot f_{sw} \quad (8)$$

The RCDM parameters in Formula (8) are:

Table 7 — Reference parameters for Formula (8)

Abbreviation	Description	RCDM parameter value	Unit
E_T	Switching loss energy of the power transistor (IGBT) per volt and per ampere	$7,5 \cdot 10^{-7}$	$\frac{J}{V \cdot A}$
U_{DC}	CDM DC link voltage	540	V
I_{motor_cable}	motor cable current, relevant for increased switching losses	$I_{motor_cable}=4$ for $I_{r,out} \leq 4A$ $I_{motor_cable}=I_{r,out}$ for $4A < I_{r,out} < 10A$ $I_{motor_cable}=10$ for $I_{r,out} \geq 10A$	A
f_{sw}	CDM switching frequency	4000 for a CDM up to 90kW 2000 for a CDM above 90kW	Hz

The variable in Formula (8) is again the inverter output current I_{out} . The switching losses do not depend on the motor speed.

If the inverter output frequency was identical to 0Hz for all operating time of the CDM, Formula (8) would not be correct anymore. However, it can be assumed that for nearly all applications at least a small output frequency different from 0Hz, e.g. 0,05Hz, will be found, so Formula (8) shall be used for all applications.

5.2.2.5 Free wheeling diode switching losses

The diode switching losses shall be calculated in the same way:

$$P_{L,sw,D} = \frac{E_D}{\pi} \cdot U_{DC} \cdot \sqrt{2} \cdot (I_{out} + I_{motor_cable}) \cdot f_{sw} \quad (9)$$

The RCDM parameters in Formula (9) are:

Table 8 — Reference parameters for Formula (9)

Abbreviation	Description	RCDM parameter value	Unit
E_D	Switching loss energy of the power diode per volt and per ampere	$2,5 \cdot 10^{-7}$	$\frac{J}{V \cdot A}$

5.2.2.6 Output inverter total losses

The losses calculated in the Formulae (6) to (9) define the losses created in an individual power semiconductor. The sum of the output inverter losses shall be calculated for a three phase CDM with six transistors and diodes as follows:

$$P_{L,inverter} = 6 \cdot (P_{L,on,T} + P_{L,on,D} + P_{L,sw,T} + P_{L,sw,D}) \quad (10)$$

5.2.3 Input converter losses

5.2.3.1 Active infeed converter

If the input converter section consists of an active infeed converter, its losses shall be calculated in an identical way as the output inverter section. In this case, the output current of the active infeed converter is the mains current of the CDM.

The output frequency of the active infeed converter is identical to the mains frequency. This limits the possible values for the modulation index m close to 1. The displacement factor between fundamental input current and fundamental input voltage is close to 1 in case of motor operation of the CDM or to -1 in case of regenerative operation. Due to this displacement factor, the CDM input current is lower than the CDM output current for AIC infeed converters, it corresponds to $I_{out} \cdot m \cdot \cos \phi$.

The reference CDM is assumed not to contain an active infeed converter, but a diode rectifier.

5.2.3.2 Diode rectifier

The fundamental of the CDM input current is proportional to the active CDM output power and is calculated by the product of the inverter output current, output phase angle and modulation index. The rms value of the CDM input current is furthermore proportional to a factor $1/\lambda$. The factor λ , being defined in Formula (B.2) as ratio of the active input power to the apparent input power of the CDM, is proportional to the displacement factor between CDM input current and decreasing with the harmonic content of the input current waveform. Standard values of λ for different rectifier topologies are given in B.4.2.

Finally, the rectifier losses shall be calculated according to Formula (11):

$$P_{L,rectifier} = 6 \cdot \left(\frac{\sqrt{2}}{\pi} \cdot m \cdot \cos \phi \cdot I_{out} \cdot U_{D,th,rectifier} + \frac{U_{D,r,rectifier} - U_{D,th,rectifier}}{\cos \phi_r \cdot I_{r,out}} \cdot \frac{\left(\frac{m \cdot \cos \phi \cdot I_{out}}{\lambda} \right)^2}{2} \right) \quad (11)$$

The RCDM parameters in Formula (11) are:

Table 9 — Reference parameters for Formula (11)

Abbreviation	Description	RCDM parameter value	Unit
$U_{D,th,rectifier}$	Threshold voltage of the rectifier power diode	0,9	V
$U_{D,r,rectifier}$	On state voltage of the rectifier power diode at rated CDM input current	2,2	V
λ	Power factor of the CDM input current and voltage	0,7	

The variables in Formula (11) are:

Table 10 — Variables for Formula (11)

Abbreviation	Description	Unit
ϕ_r	phase angle between fundamental CDM output voltage and fundamental CDM output current at rated torque according to Table 3	°

5.2.4 Input choke losses

Input chokes are sometimes used to reduce harmonics. The inductance of the choke decreases with higher input power of the converter. Typically, the impedance of the input choke is chosen to be a certain part $k1_{choke}$ of the rated inverter impedance U_{mL1}/I_{equ} . Assuming the voltage drop at the resistive part of the input choke to be a certain part $k2_{choke}$ of the overall voltage drop on the input choke, the losses in the input choke shall be calculated to

$$P_{L,choke} = k1_{choke} \cdot k2_{choke} \cdot 3 \cdot \frac{\left(\frac{m \cdot \cos \phi \cdot I_{out}}{\lambda} \right)^2}{\cos \phi_r \cdot I_{r,out}} \cdot U_{mL1} \quad (12)$$

The RCDM parameters for the reference converter in Formula (12) are:

Table 11 — Reference parameters for Formula (12)

Abbreviation	Description	RCDM parameter value	Unit
$k1_{choke}$	choke impedance, relative to the rated CDM impedance	0,02	
$k2_{choke}$	relative voltage drop on the resistive part of the choke	0,25	
U_{mL1}	Phase to ground voltage of the supply network	230	V

The losses of DC chokes can be calculated in the same way as the losses for AC chokes.

The losses of low frequency line harmonic filters are calculated in the same way, because the major part of these losses is generated in the choke and losses in the filter capacitors can be neglected.

5.2.5 DC link losses

As explained in B.5, the DC link losses are mainly generated by resistors which are required to ensure a proper voltage sharing between the DC link capacitors and by the equivalent series resistor inside each capacitor. In a first order approximation, the amount of DC link capacitance is proportional to the rated inverter power. Consequently, the load independent losses in the resistors in parallel to the capacitors are proportional to the rated inverter output current as well. Furthermore, they are proportional to the square of the DC link voltage. The losses in the equivalent series resistor of the capacitor depend on the square of the AC part of the rectifier output current. Losses caused by high frequency inverter current are small enough to be neglected. The DC link losses shall finally be calculated by:

$$P_{L,dc_link} = k1_{DC_link} \cdot I_{r,out} \cdot U_{DC}^2 + k2_{DC_link} \cdot \frac{\left(\frac{\sqrt{3}}{1,35} \cdot \frac{m \cdot \cos \phi \cdot I_{out}}{1 + 50 \cdot k1_{choke}} \right)^2}{I_{r,out}} \quad (13)$$