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**Adjustable speed electrical power drive systems –
Part 9-2: Ecodesign for power drive systems, motor starters, power electronics
and their driven applications – Energy efficiency indicators for power drive
systems and motor starters**

**Entraînements électriques de puissance à vitesse variable –
Partie 9-2: Écoconception des entraînements électriques de puissance, des
démarreurs de moteurs, de l'électronique de puissance et de leurs applications
entraînées – Indicateurs d'efficacité énergétique pour les entraînements
électriques de puissance et les démarreurs de moteurs**



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électriques de puissance et les démarreurs de moteurs**

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

ADJUSTABLE SPEED ELECTRICAL POWER DRIVE SYSTEMS –**Part 9-2: Ecodesign for power drive systems,
motor starters, power electronics and their driven applications –
Energy efficiency indicators for power drive systems and motor starters**

FOREWORD

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International Standard IEC 61800-9-2 has been prepared by subcommittee 22G: Adjustable speed electric drive systems incorporating semiconductor power converters, of IEC technical committee 22: Power electronic systems and equipment.

The text of this document is based on the following documents:

FDIS	Report on voting
22G/349/FDIS	22G/352/RVD

Full information on the voting for the approval of this document can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2

A list of all parts in the IEC 61800 series, published under the general title *Adjustable speed electrical power drive systems*, can be found on the IEC website.

The committee has decided that the contents of this publication will remain unchanged until the stability date indicated on the IEC website under "<http://webstore.iec.ch>" in the data related to the specific publication. At this date, the publication will be

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INTRODUCTION

This part of IEC 61800 has been developed to allow evaluation of power losses of CDMs (complete drive modules) and PDSs (power drive systems).

The requirements for measuring energy efficiency of motors with non-sinusoidal supply are under the responsibility of IEC/TC 2 and will be published under the IEC 60034 series.

IEC SC 22G includes the standardization task force for dealing with this topic. It has close collaboration with several other technical committees (for example, IEC TC 2, IEC SC 121A).

IEC SC 22G maintains responsibility for 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 core requirements of energy efficiency standardization are illustrated in Figure 1. The work has been agreed to provide the reasonable target as a best compromise.

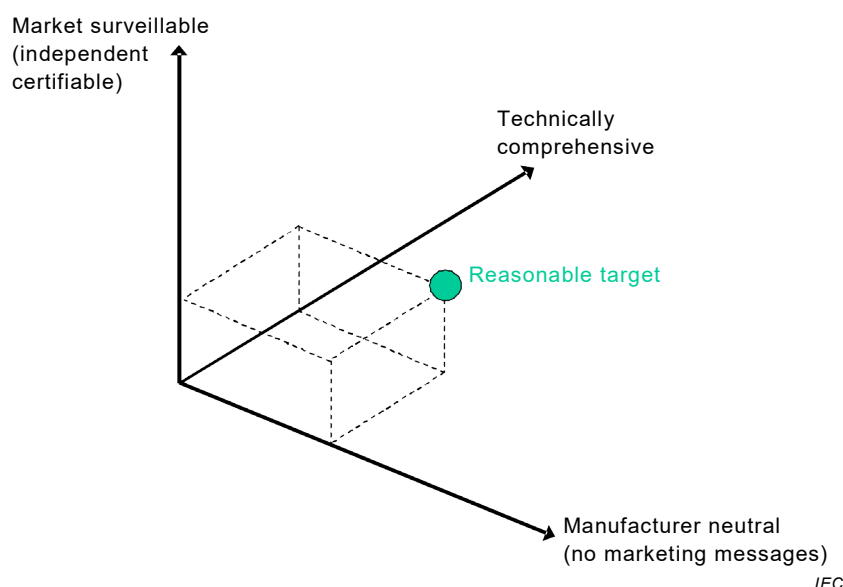


Figure 1 – Illustration of core requirements of energy efficiency standardization

IEC 61800 (all parts) does not deal with mechanical engineering components.

NOTE Geared motors (motors with directly adapted gearboxes) are treated like power drive systems (converter plus motor). See IEC 60034-30-1 for classification of the losses of a geared motor. The efficiency classes of gearboxes as individual components are under consideration.

IEC 61800-9-2 is a subpart of the IEC 61800 series, which has the following structure:

- *Part 1: General requirements – Rating specifications for low voltage adjustable speed DC power drive systems*
- *Part 2: General requirements – Rating specifications for low voltage adjustable speed AC power drive systems*
- *Part 3: EMC requirements and specific test methods*
- *Part 4: General requirements – Rating specifications for AC power drive systems above 1 000 V AC and not exceeding 35 kV*
- *Part 5: Safety requirements*

- *Part 6: Guide for determination of types of load duty and corresponding current ratings*
- *Part 7: Generic interface and use of profiles for power drive systems*
- *Part 8: Specification of voltage on the power interface*
- *Part 9: Ecodesign for power drive systems, motor starters, power electronics and their driven applications*

Each part is further subdivided into several subparts, published either as International Standards or as Technical Specifications or Technical Reports, some of which have already been published. Other will be published with the part number followed by a dash and a second number identifying the subdivision (example: IEC 61800-9-2).

It considers basic requirements from the EN 50598-2 CENELEC standard published on 2014-12-19 and considers also the following key points in cooperation with relevant technical committees.

It has been developed in close collaboration with other technical committees (IEC TC 2, IEC SC 121A) and with a customer's stakeholder committee CEN/TC 197 in order to provide a comprehensive standard for energy efficiency and ecodesign requirements.

Key points:

- Requirements for energy-efficient design of electric drive systems in accordance with the driven load
- Requirements and IE-classification of complete drive modules (CDM)
- Requirements and IES-classification of power drive systems (PDS)
- Determination of PDS losses and requirements for the link to the driven equipment for the determination of energy efficiency classification/evaluation of the extended product
- Requirements for an environmentally conscious system design and environmental declaration of a motor system

ADJUSTABLE SPEED ELECTRICAL POWER DRIVE SYSTEMS –

Part 9-2: Ecodesign for power drive systems, motor starters, power electronics and their driven applications – Energy efficiency indicators for power drive systems and motor starters

1 Scope

This part of IEC 61800 specifies energy efficiency indicators of power electronics (complete drive modules, CDM), power drive systems (PDS) and motor starters, all used for motor driven equipment.

It specifies the methodology for the determination of losses of the complete drive module (CDM), the power drive system (PDS) and the 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 document proposes a methodology for the implementation of the best energy efficiency solution of drive systems. This depends on the architecture of the motor driven system, on the speed/load profile and on the operating points over time of the driven equipment.

The methodology of the extended product approach and the semi analytical models are defined in IEC 61800-9-1.

The structure of this document is as follows:

- the losses of standardized reference PDS (RPDS), standardized reference CDM (RCDM) and the mathematical model for their calculation are given and classified;
- the reference 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 the determination of the losses of a real PDS and a real CDM are given and compared to the reference RPDS and RCDM;
- the requirements for type testing and user documentation are given;
- some exemplary losses of an overall system are illustrated 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 voltage (100 V up to and equal to 1 000 V), single axis AC/AC power drive systems with three-phase motors. Geared motors are treated as standard motors when motor and gearbox can be separated.

All provided reference data is derived from PDS with induction motors. It may be used for all types of PDS with other types of motors as well.

The application of this document to the following equipment may be technically possible but is not mandatory:

- High voltage CDM and PDS with a rated voltage above 1 000 V AC;
- Low voltage CDM and PDS with a rated voltage below 100 V AC;

- High power PDS above a rated power of 1 000 kW;
- High power CDM above a rated apparent output power of 1 209 kVA;
- Low power PDS below a rated power of 0,12 kW;
- Low power CDM below a rated power of 0,278 kVA;
- CDMs other than those converting electrical AC power into one single AC output;
- PDSs other than those converting electrical AC power into one single mechanical rotating shaft;
- PDSs and CDMs that are able to regenerate energy back into the AC power supply;
- PDSs and CDMs having an input current with a THC (according to the definition in IEC 61000-3-12) of less than 10 %;
- PDS with geared motors where motor and gearbox cannot be separated, for example because of a common housing,
- Servo PDS (consisting of frequency converter, motor and position feedback sensor);
- PDSs that are not put on the market as one single product.

NOTE IEC 61800-9 (all parts) does not cover energy efficiency classification of driven equipment but provides input for the assessment according to the extended product approach.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60038:2009, *IEC standard voltages*

IEC 60050-161, *International Electrotechnical Vocabulary – Part 161: Electromagnetic compatibility*

IEC 60034-1, *Rotating electrical machines – Part 1: Rating and performance*

IEC 60034-2-1:2014, *Rotating electrical machines – Part 2-1: Standard methods for determining losses and efficiency from tests (excluding machines for traction vehicles)*

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 60034-30-1, *Rotating electrical machines – Part 30-1: Efficiency classes of line operated AC motors (IE Code)*

IEC 60947-4-1, *Low voltage switchgear and controlgear – Part 4-1: Contactors and motor-starters – Electromechanical contactors and motor-starters*

IEC TS 61800-8, *Adjustable speed electrical power drive systems – Part 8: Specification of voltage on the power interface*

IEC TS 62578, *Power electronics systems and equipment – Operation conditions and characteristics of active infeed converter (AIC) applications including design recommendations for their emission values below 150 kHz*

3 Terms, definitions, symbols and abbreviated terms

3.1 Terms and definitions

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

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at <http://www.electropedia.org/>
- ISO Online browsing platform: available at <http://www.iso.org/obp>

3.1.1

active infeed converter

AIC

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

Note 1 to entry: See IEC TS 62578.

Note 2 to entry: The IEC defines terms (VSC and CSC) as voltage stiff AC/DC converter [551-12-03] and current stiff AC/DC converter [551-12-04]. Most of the AICs are bi-directional converters and have sources on the DC side. Therefore, they are known as voltage source converters and current source converters.

3.1.2

AEDM

alternate efficiency determination method

analytical model used by motor manufacturers for calculation of the losses that can be used to determine the energy efficiency index of an extended product

3.1.3

CDM

complete drive module

drive

drive controller

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.

3.1.4

crest factor

ratio of the peak absolute value to the RMS value of the waveform

3.1.5

driven equipment

equipment mechanically connected to the shaft of a motor

3.1.6

EEl

value describing the energy efficiency of an application, resulting from the extended product approach (EPA)

Note 1 to entry: If the extended product is a pump system, the EEl is the ratio of the demanded energy (actual plus losses) to the theoretical energy required for the application.

3.1.7**extended product****EP**

driven equipment together with its connected motor system (e.g. a PDS)

Note 1 to entry: See Figure 2

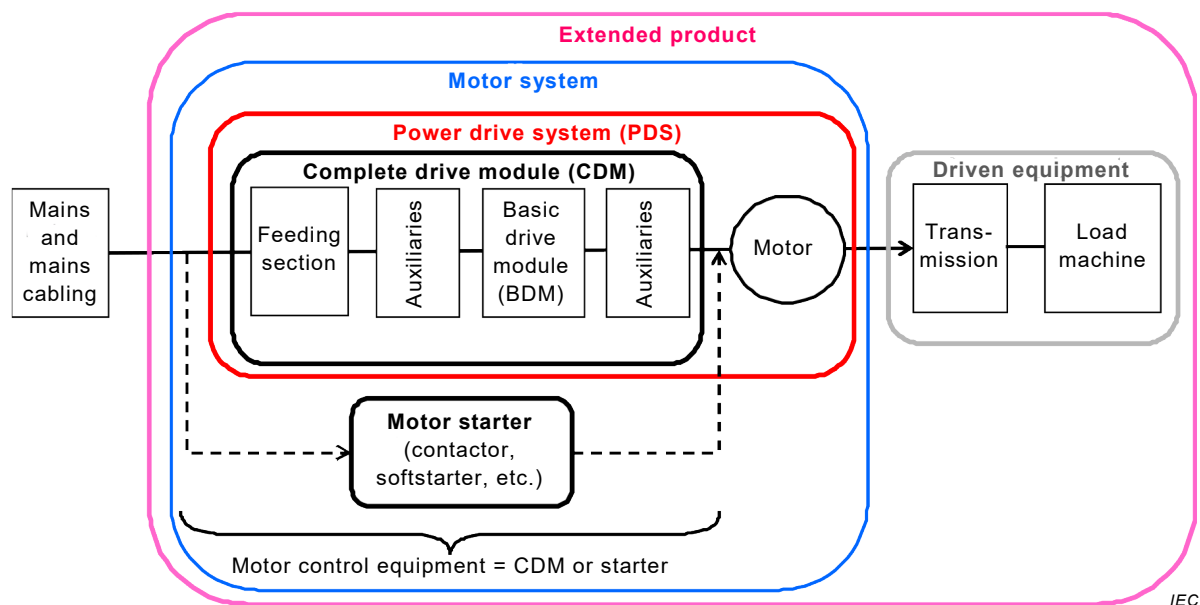


Figure 2 – Illustration of the extended product with included motor system

3.1.8**IE class**

efficiency classification of components of a motor system (3.1.10)

Note 1 to entry: IE is an abbreviation for "international efficiency".

3.1.9**IES class**

efficiency classification of a motor system (e.g. PDS or a gear drive motor)

Note 1 to entry: IES is an abbreviation for "international efficiency of systems".

3.1.10**motor system**

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

3.1.11**PDS****power drive system**

system consisting of a CDM and a motor

3.1.12**pulse pattern**

pattern of the switched phase-to-phase voltage or phase current at the unfiltered output terminals of the converter, resulting from pulse frequency and modulation scheme

3.1.13

reference complete drive module

RCDM

complete drive module defined by mathematical equations and/or power losses

Note 1 to entry: It is used as a basis for determining the IE class of an individual CDM.

3.1.14

reference motor

RM

motor defined by mathematical equations and/or power losses

Note 1 to entry: It is used as a basis for comparing other motors.

3.1.15

reference power drive system

RPDS

combination of the reference motor and the reference PDS

3.1.16

servo PDS

closed-loop controlled electric drive system for precise and dynamical control of angular or linear position, velocity and acceleration for the driven servomechanism in typical applications such as CNC machinery, automated manufacturing or robotics

Note 1 to entry: See Figure 3.

Note 2 to entry: It consists of a frequency converter, a motor and a position feedback sensor.

Note 3 to entry: Such servo applications are characterised with non-periodically (duty type S9) or periodically variable load and speed within the permissible 4-quadrant operating range ($\pm T_{MAX}$, $\pm n_{MAX}$) and includes frequently applied operation in overload ($T > T_N$) and/or field weakening range ($n > n_N$) of the motor (see diagram below).

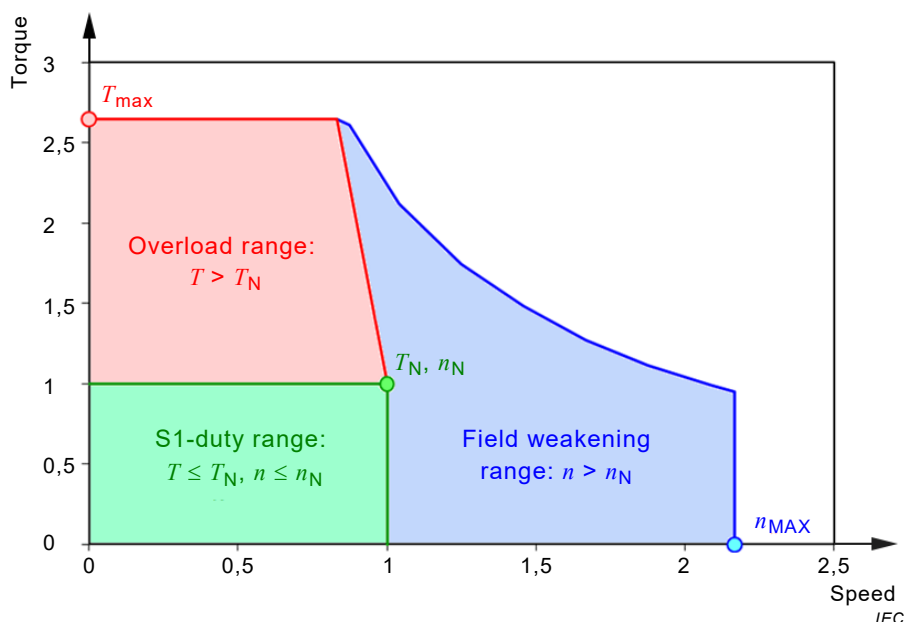


Figure 3 – Torque-speed-characteristic of servo PDS

3.1.17

single axis

single mechanical output shaft of an individual motor

Note 1 to entry: Applies to CDM supplying one motor or PDS that includes only one motor.

3.1.18**test load**

electrical device that determines the output current I_{out} and the 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.

3.1.19**test load current**

total apparent current into the test load to produce a certain torque (see Table 1)

3.1.20**torque-producing current**

part of the test load current (see 3.1.19) that produces a certain torque (see Figure 6, Table 1)

Note 1 to entry: For an asynchronous motor, the torque-producing current is the rotor current.

3.2 Symbols and abbreviated terms**3.2.1** c_{liquid}

specific heat capacity of liquid

3.2.2 E_{D}

switching loss in 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}

number of switching events of one semiconductor within one second

Note 1 to entry: It determines, together with the selected pulse pattern and the converter topology, the lowest frequency of non-controllable harmonics or inter-harmonics at the IPC (in-plant point of coupling) or the motor.

Note 2 to entry: To turn on and turn off the semiconductor's switch are separate switching events. Thus, the switching frequency of a two level converter is two times the pulse frequency (also called the carrier frequency) of the phase-to-phase voltage for modulation that uses continuous switching and about 1,33 times the pulse frequency of the phase-to-phase voltage for modulation that uses discontinuous switching.

3.2.5 $I_{\text{motor_cable}}$

current in the motor cable of one power port (see IEC 61800-2) of the PDS, used for calculating switching losses

Note 1 to entry: This typically 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

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

$k^2_{\text{DC_link}}$
load dependent DC link loss parameter ($\Omega \cdot A$)

3.2.14

k^2_{choke}
relative voltage drop on the resistive part of the choke

3.2.15

K_{fe}
Additional/split iron losses in a motor

3.2.16

K_{fw}
Additional/split of friction and windage losses in a motor

3.2.17

K_{LL}
Distribution of load losses

3.2.18

k_{VD}
ratio of rated motor voltage to maximum CDM output voltage

3.2.19

$P_{\text{L,cooling}}$
power losses generated by the cooling equipment of a CDM (e.g. fan losses), in relation to the BDM (see IEC 61800-2) losses if the CDM needs to be separately cooled

3.2.20

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

3.2.21

n_i
speed [rpm] at load point i

3.2.22

n_r
rated speed [rpm]

3.2.23

P_i
power consumption [kW] at load point i

3.2.24

$P_{in,CDM}$
input power of the CDM obtained from the power loss measurement

3.2.25

$P_{in,PDS}$
input power of the PDS obtained from the power loss measurement

3.2.26

P_{Lfe}
iron losses of a motor

Note 1 to entry: See also IEC 60034-2-1.

3.2.27

P_{Lfw}
friction and windage losses of a motor

Note 1 to entry: See also IEC 60034-2-1.

3.2.28

P_{LHL}
additional harmonic losses of a motor caused by non-sinusoidal power supply

Note 1 to entry: see also IEC 60034-2-3.

3.2.29

P_{LL}
additional load losses of a motor

Note 1 to entry: see also IEC 60034-2-1.

3.2.30

p_L RM
relative losses of the reference motor

3.2.31

P_L RM
losses of the reference motor

3.2.32

P_{LR}
rotor losses of a motor

Note 1 to entry: see also IEC 60034-2-1

3.2.33

P_{LS}
stator winding losses of a motor

Note 1 to entry: See also IEC 60034-2-1.

3.2.34

P_{LTsin}
total losses of a motor at sinusoidal power supply

Note 1 to entry: According to IEC 60034-2-1:2014, method 2-1-1B.

3.2.35

$P_{LT,Mot}$
total losses of a motor when supplied by a converter (non-sinusoidal power supply)

Note 1 to entry: According to IEC 60034-2-1:2014, method 2-1-1B.

3.2.36

$P_{out,CDM}$
output power of CDM obtained from the power loss measurement

3.2.37

$P_{out,PDS}$
output power of PDS obtained from the power loss measurement

3.2.38

P_r
rated power of equipment which is assigned by its manufacturer

3.2.39

P_{proc}
power demand of the mechanical or fluid-mechanical process

3.2.40

P_L
electrical power losses

Note 1 to entry: In $P_{L,CDM}$, $P_{L,Mot}$, $P_{L,PDS}$ and $P_{L,Aux}$, the index CDM refers to the complete drive module; Mot refers to the motor, PDS to the power drive system and Aux to the auxiliary devices like cables, transformers or filters.

3.2.41

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

3.2.42

$P_{L,CDM}$
power losses of a CDM

3.2.43

$P_{L,CDM, determined}$
power losses of CDM from the power loss determination method

3.2.44

$p_{L,CDM}$
relative power losses of the CDM, in relation to its rated apparent power

3.2.45

$P_{L,choke}$
power losses in the choke section of a CDM

3.2.46 $P_{L,control}$

power losses in the control section of a CDM

3.2.47 P_{L,DC_link}

power losses of the DC link section of the CDM

3.2.48 $P_{L,inverter}$

power losses in the inverter section of a CDM

3.2.49 $P_{L,PDS, determined}$

power losses of the PDS from the power loss determination method

3.2.50 $P_{L,rectifier}$

power losses in the rectifier section of a CDM

3.2.51 $P_{L,resistor}$

measured power losses of the resistor in comparative calorimetric measurement

3.2.52 $P_{L,on,D}$

on state power losses of a power diode

3.2.53 $P_{L,on,D, rectifier}$

on state power losses of a rectifier diode

3.2.54 $P_{L,on,T}$

on state losses of a power transistor

3.2.55 P_{LSR}

the stator and rotor winding losses of the motor

3.2.56 $P_{L,sw,D}$

switching power losses of a power diode

3.2.57 $P_{L,sw,T}$

switching power losses of a power transistor

3.2.58 $P_{r,M}$

rated power of a motor

Note 1 to entry: In IEC 60034 (all parts) related to motors, this is named P_N .

3.2.59

$P_{L, \text{stby}}$
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.

3.2.60

P_N
relative output losses of a motor

3.2.61

Q
flow rate of a pump unit

3.2.62

Q_{BEP}
flow rate of the pump at the best efficiency point

3.2.63

Q_{cooler}
volumetric flow rate of the cooler in the calorimeter

3.2.64

Q_{ISI}
interpolation error (stability index)

3.2.65

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

3.2.66

$S_{r, \text{equ}}$
rated apparent power of a piece of equipment

3.2.67

$S_{r, \text{RCDM}}$
rated apparent power of the reference CDM

3.2.68

T
the torque of a motor

3.2.69

t_w
working time of an equipment

3.2.70

T_i
torque [Nm] at operating point i

3.2.71

$U_{1, r, \text{out}}$
fundamental rated line-to-line CDM output voltage

Note 1 to entry: For the reference CDM, this value is assumed to be 400 V unless stated otherwise.

3.2.72

U_{DC}
DC link voltage of a CDM

3.2.73

$U_{D,r}$
on state voltage of a power diode at rated CDM current

3.2.74

$U_{D,r,rectifier}$
on state voltage of a rectifier diode at rated CDM current

3.2.75

$U_{D,th}$
threshold voltage of a power diode

3.2.76

$U_{D,th,rectifier}$
threshold voltage of a rectifier diode

3.2.77

U_{mL1}
line to neutral voltage of the power supply system in phase L1

3.2.78

$U_{T,r}$
on state voltage of a power transistor at rated CDM current

3.2.79

$U_{T,th}$
threshold voltage of a power transistor

3.2.80

W_w
electrical energy demand of extended product during working time

3.2.81

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

3.2.82

$\Delta p_{L,CDM}$
uncertainty [%] of power loss determination method for CDM

3.2.83

$\Delta P_{L,CDM}$
uncertainty [W] of power loss determination method for CDM

3.2.84

$\Delta p_{L,PDS}$
Uncertainty [%] of power loss determination method for PDS

3.2.85

$\Delta P_{L,PDS}$
uncertainty [W] of power loss determination method for PDS

3.2.86

θ_{in}

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

3.2.87

θ_{inside}

temperature of cooling air between two calorimetric measurement chambers

3.2.88

θ_{out}

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

3.2.89

φ

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

3.2.90

Φ

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

3.2.91

Φ_r

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

4 Reference PDS (RPDS), reference CDM (RCDM) and reference motor (RM)

4.1 General

In order to determine the most efficient extended product for a given application, a direct comparison of several drives topologies and/or several control strategies is required. The extended product approach described in IEC 61800-9-1 allows for this.

To support this approach, the concept of "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 the designed extended product to an average technology PDS.

The definition of the RPDS is generic and independent of a specific product or manufacturer.

It allows

- setting the limiting values for classifications,
- classification of the real PDS in comparison to the RPDS,
- classification of the CDM,
- application of IEC TS 60034-30-2,
- classification of converter-fed motors and motors classified per IEC 60034-30-1,
- limiting the assessment to only a few appropriate measured or calculated load points, and
- determining the energy consumption of various driven applications.

Examples of relevant input values (load points) for classification of different driven applications:

Loads with square-law torque-speed characteristics (e.g. most pump units) will typically require relative losses or input powers P_1 at the load points $p_{L, PDS (50; 25)}$, $p_{L, PDS (100; 50)}$ and $p_{L, PDS (100; 100)}$ for calculation of the losses of the motor system. The permissible loss tolerance is $\pm 10\%$ of the losses in each operating point.

Constant torque loads (e.g. hoisting equipment) will need the additional 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 motor system.

4.2 Reference operating points of the RPDS, RCDM, RM and associated losses

All driven equipment can be described by the power required by the machine/application. The power requirements are the product of torque and speed at any working point. 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 4, for the RM in Figure 5 and for the RCDM in Figure 6.

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 of rated mechanical output power to electrical input power (including the losses).

In this document, losses related to the nominal output power of the power drive system (p in %) are considered instead of efficiency. This is done 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.

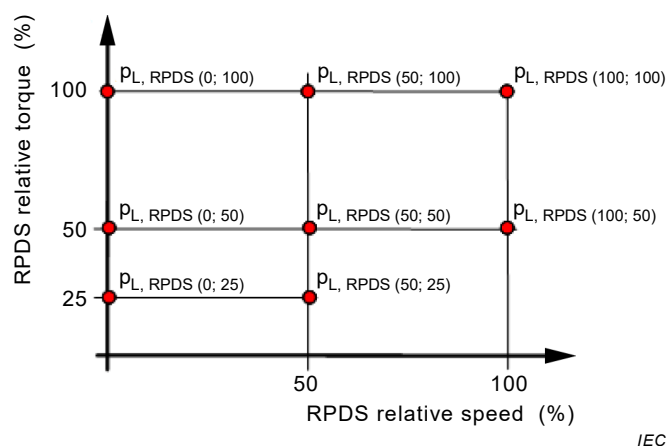


Figure 4 – Illustration of the operating points (shaft speed, torque) for the determination of relative losses of the power drive system (RPDS)

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 load points of Figure 5 and Figure 6 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 Equation (19) has to be used.

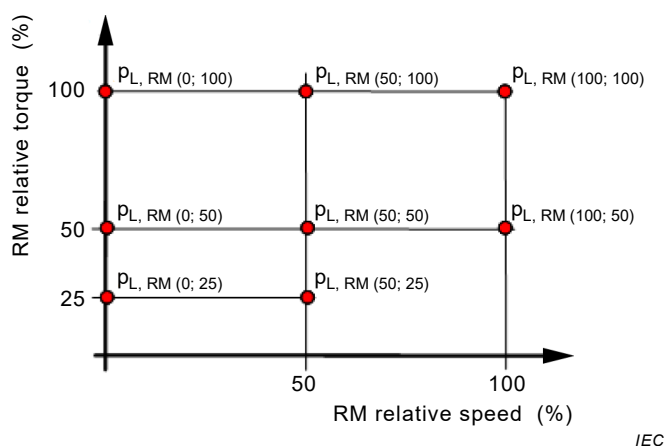


Figure 5 – Illustration of the operating points (shaft speed, torque) for the determination of relative losses of the reference motor (RM)

The load points of the reference CDM (RCDM) cannot be given as a percentage of speed and torque of the corresponding rated values as the CDM provides only currents and voltages at its output. To allow a reproducible comparison and to avoid overmodulation, the fundamental AC output voltage shall be limited to 90 % of the AC input voltage.

NOTE 1 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.

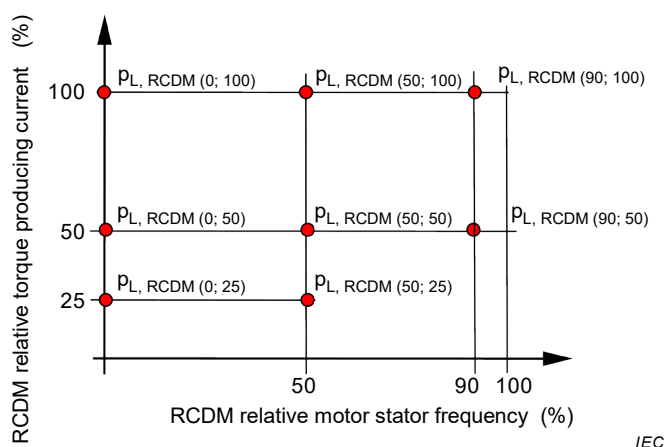


Figure 6 – Illustration of the operating points (relative motor stator frequency, relative torque-producing current) for the determination of losses of the reference complete drive module (RCDM)

NOTE 2 For asynchronous motors, the torque-producing current is the rotor current. The relation between the overall motor current and the torque producing current is given in Table 1.

NOTE 3 For physical reasons, the illustrated load points on the y-axis of Figure 6 $p_{L,RCDM}(0, n)$ are achieved only with a non-zero output voltage in order to let current flow through the resistance of the motor windings.

The relative fundamental CDM output voltage (in per cent) shall not be lower than the relative CDM output frequency (in per cent).

If required, the losses for intermediate operating points may be determined by one of the calculation methods presented in E.2.1:

- a) maximum losses in neighbouring, predefined load points;
- b) two-dimensional linear interpolation between neighbouring load points;
- c) loss calculation of the CDM according to the mathematical model described in 5.2.

Motor losses are interpolated according to Annex D.

A deviation of the relative rotor speed from the defined load points (see Figure 4) of up to the rated slip is allowed. At 0 Hz, a deviation of up to 12 Hz shall be allowed.

For losses at additional load points and at part load conditions and reduction of operating points, see 8.4 and D.4.3.

4.3 Combining PDS losses with the driven equipment – 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 for determining the efficiency classification of an extended product is shown in Figure 7.

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 2 (left hand side of Figure 5) is defined in this document, whereas the semi analytical energy consumption models of the PDS-driven application (right hand side of Figure 5) shall be drafted by their responsible product committees by using the same approach. An example for PDS driven pump units is given in IEC 61800-9-1. Figure 8 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.

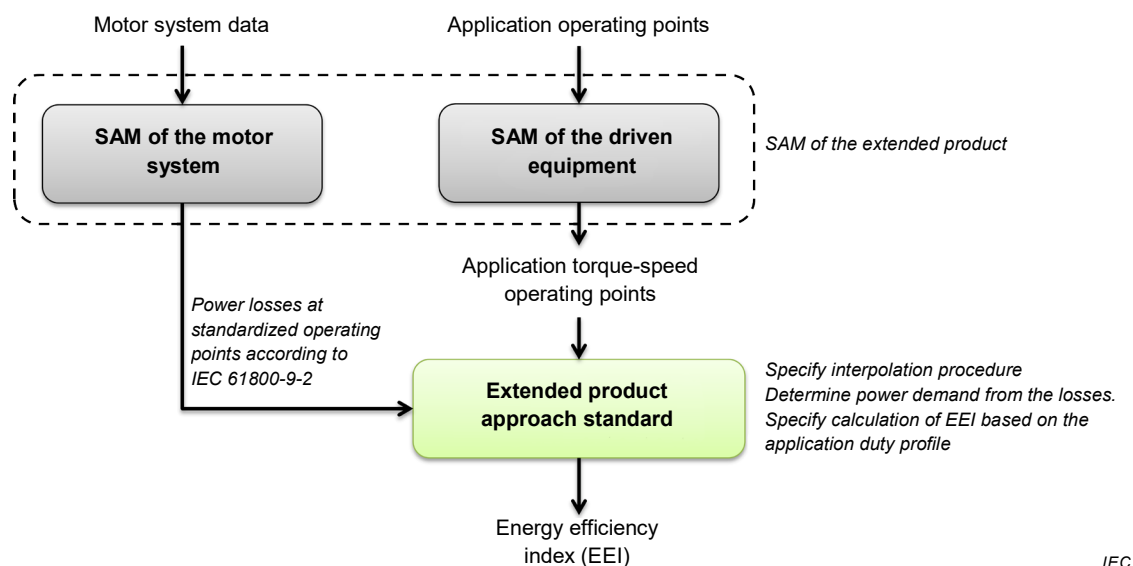
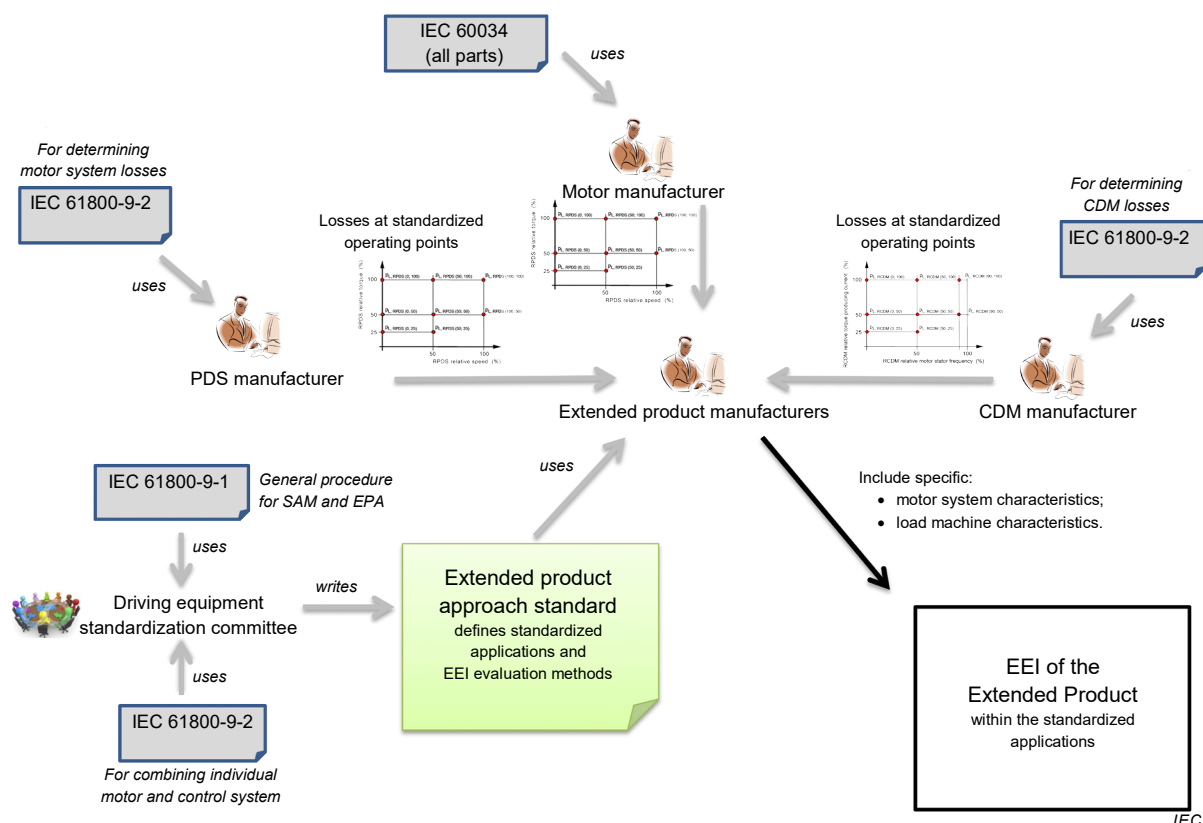


Figure 7 – Illustration of the workflow to determine the energy efficiency index (EEI) of an extended product

This document 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.



Motor and CDM manufacturers can provide data directly to the motor system manufacturer.

If the motor system is based on a starter, then only the motor losses are needed as input to the EPA.

Figure 8 – Illustration how to combine different data sources to determine the energy efficiency index (EEI) of an extended product

4.4 IE classes of line-fed motors

IEC 60034-30-1 defines IE classes for motors operated direct-on-line from IE1 up to IE4 (or IE5 respectively). The range above IE5 is currently not in use.

4.5 IE classes of converter-fed motors

According to IEC TS 60034-2-3, the harmonic voltage contents of CDM increases motor losses by about 15 % to 25 %.

Motors not designed to be supplied directly from mains for operation (DOL, direct on line) will be classified with an IE-class according to their losses at rated speed and torque (rated power) according to IEC TS 60034-30-2.

The IE Class for motors that are capable of running DOL is defined for fixed speed operation from IEC 60034-30-1 or for motors that could run when fed from CDM as defined from IEC TS 60034-30-2. Losses for the defined 7 operating points can be extrapolated from Annex D. Losses for these points should be provided by the motor manufacturer per the alternative efficiency determination method (AEDM) determined by using IEC 60034-2-3.

4.6 IE Classes of frequency converters (complete drive modules, CDM)

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 4.2.

AIC according to IEC TS 62578, which are CDMs with the ability to feed braking energy from the inertia of the load back to the electric power supply system, can be excluded from the IE classification. The relative losses of such AIC's 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 a mains current THC of 10 % or lower (according to IEC 61000-3-12), for example power factor correction (PFC) fed CDMs, can be excluded from the IE classification. The relative losses of an active rectifier are typically twice the losses of a CDM with a diode rectifier. However, the efficiency contribution of an active rectifier can be seen in improved power grid utilization and lower system level losses and disturbances (power transformer, cabling, voltage harmonics, flicker).

4.7 IES Classes of a PDS

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 in this document. Limiting values of classes IES3 to IES9 may be given in future editions of this document.

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 reference PDS (RPDS) (see Figure 4) shall be classified as IES1.

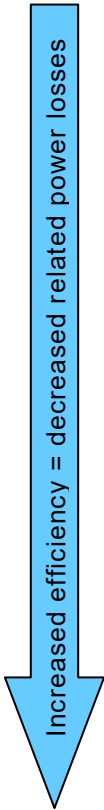
4.8 Consistency of IE and IES classes

It is important to understand that the IE classes of individual components such as converter-fed motors, grid operated motors or CDMs cannot be added in order to determine the IES class of a PDS.

The IES classification of PDSs can only be determined by the procedures laid out in 4.9 with a detailed knowledge of the losses of all components.

Individual IE classes are required for the classification of components without prior knowledge of the EP.

Generally, higher IE classes will demonstrate increased efficiency or decreased relative power losses.



Line fed motors Efficiency	Converter fed motors Efficiency	Converters (CDM) losses related to rated power	Power drive system (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 ± 25 %	IES1 – reference value ± 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.

Key

u.c. under consideration

NOTE IE classes for line fed motors are defined in IEC 60034-30-1. IE classes for converter fed motors will be defined in IEC TS 60034-30-2.

Figure 9 – Metrical relation of IE, IES classes

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

Methods for the determination of losses and IE classes of a motor are given in IEC 60034-30 (all parts) – see also Figure 9. Manufacturers may also define an IES class for a PDS that is using their motor. In that case, the manufacturer shall determine the relative losses of his motor when operated on a RCDM.

A CDM manufacturer shall declare the losses of his dedicated CDM and display an IE class according to Figure 9. The manufacturer may also declare an IES class for a PDS equipped with his CDM. In that case, the manufacturer shall measure or calculate the losses of his CDM. When real motor data is not available, the losses of the RM shall be used.

The CDM manufacturer may provide information in the documentation which determination methods described in Clause 7 have been used. This includes the expected IES classes for different combinations of a CDM and selected specific motors using the methods of this document.

Any or all available control features of the CDM may be employed to minimize losses during the PDS evaluation, and shall be reported as part of the record of evaluation.

A spreadsheet on the application of "test" and "reference" devices for the determination of IE and IES classes is shown in Figure 10. It also gives guidance to sole CDM or sole motor manufacturers regarding the determination of the IES class of a resulting PDS in combination with "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 class 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 class 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			

IEC

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

This approach allows the determination of the IES efficiency class of a final PDS even when only one component (the motor or the CDM) is available.

5 Mathematical model of CDM, motor and PDS

5.1 General

The mathematical models given in Clause 5 describe procedures for the determination of losses of the CDM, motor and PDS. They allow for the calculation of losses of a product without measurements.

The models consist of formulae, variables and parameters. The formulae describe state of the part loss calculation procedures, which are generally accepted today and 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.

If an extended product committee needs to define a typical CDM or PDS for their dedicated application(s), typical CDM or PDS parameters for those specific applications may be used. These deviations shall be provided in the extended product standard.

For the reference CDM (RCDM), reference motor (RM) and reference PDS (RPDS), reference parameters are defined respectively in 5.2, 5.3.3 and 5.4.

The procedure of the loss determination is illustrated in Clause 7.

5.2 CDM losses

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

The CDM and test load are illustrated in Figure 11.

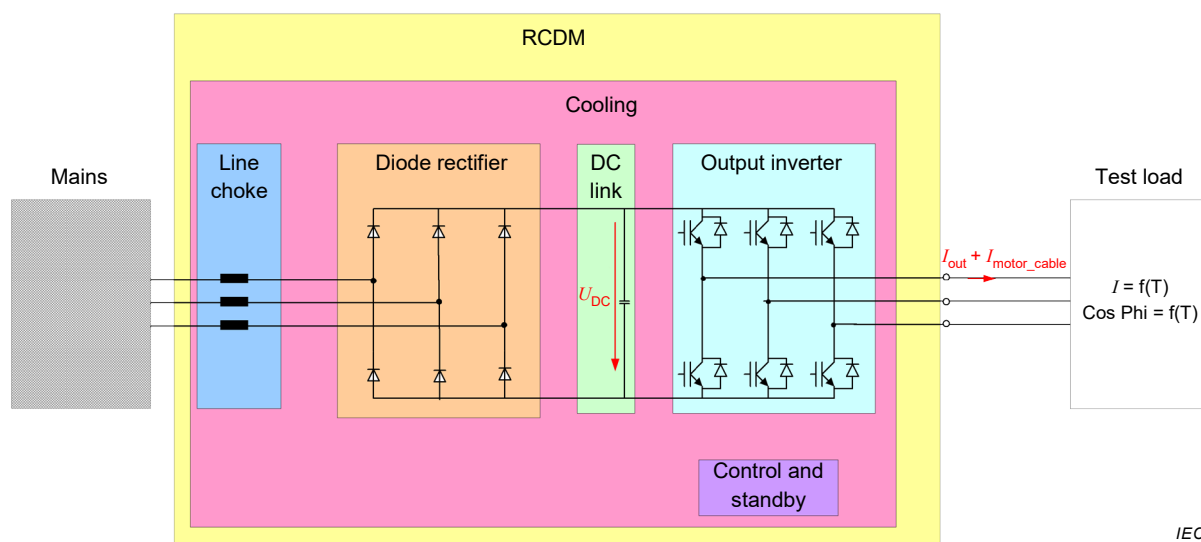


Figure 11 – Illustration of the CDM and the test load

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 fundamental output voltage, its relative fundamental output current and the phase angle between the fundamental CDM output voltage and fundamental CDM output current.

The relative output voltage is approximately the same as the relative 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 CDM output voltage remains 1,00 for all motor speeds above the nominal motor speed.

In the first step, the motor speed has to be transferred into a CDM output frequency, and the motor torque has to be converted to an CDM output current and a phase angle between the 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 being identical to the relative CDM output frequency.

For CDM evaluation, the following data obtained by measurements on real motors shall be used as a test load data for all frequencies within scope:

Table 1 – 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				
	0,278 kVA (0,12 kW) to < 1,29 kVA (0,75 kW)	1,29 kVA (0,75 kW) to < 7,94 kVA (5,5 kW)	7,94 kVA (5,5 kW) to < 56,9 kVA (45 kW)	56,9 kVA (45 kW) to < 245 kVA (200 kW)	245 kVA (200 kW) to < 1 209 kVA (1 000 kW)
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 2 – 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				
	0,278 kVA (0,12 kW) to < 1,29 kVA (0,75 kW)	1,29 kVA (0,75 kW) to < 7,94 kVA (5,5 kW)	7,94 kVA (5,5 kW) to < 56,9 kVA (45 kW)	56,9 kVA (45 kW) to < 245 kVA (200 kW)	245 kVA (200 kW) to < 1 209 kVA (1 000 kW)
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

NOTE For CDM testing, a tolerance of $\pm 0,08$ (see 7.9) of the test load displacement factors stated in Table 3 is allowed

Test load current in Table 1 and test load phase angle in Table 2 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. The test load data in Table 1 and Table 2 can be used for any CDM relative output frequency. Data for torque producing currents different from the defined operating points in Table 1 and Table 2 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 2 and the IE2 efficiency η_{nMotor} defined in IEC 60034-30-1:

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

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

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

For calculating the losses of a CDM with the input variables from Table 1 and Table 2, the analytical Formulae (5) to (16) 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 18 for the IE class determination and in Table A.1 for the eight operating points defined in Figure 6. The RCDM is based on 400V supply voltage.

In contrast to Annex B, which describes the PDS sub-frames from the mains to the load, 5.2 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.

For a real CDM, the parameter values on power semiconductors and other devices may be referred to typical values. Additionally, the model presented in 5.2 may be used for the determination of losses of a CDM by calculation. The manufacturer is allowed to use a different calculation model or loss simulations. Manufacturers are responsible to apply correct accuracies in Formula (21).

5.2.2.2 Transistor on state losses

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

$$P_{L,on,T} = \sqrt{2} \cdot I_{out} \cdot U_{T,th} \cdot \left(\left(\frac{1}{2\pi} \right) + \frac{1,22 \cdot m \cdot \cos \phi}{8} \right) + \frac{U_{T,r} - U_{T,th}}{I_{r,out}} \cdot 2 \cdot I_{out}^2 \cdot \left(\frac{1}{8} + \frac{1,22 \cdot m \cdot \cos \phi}{3\pi} \right) \quad (5)$$

The RCDM parameters in Formula (5) are given in Table 3:

Table 3 – Reference parameters for Formula (5)

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 (5) are given in Table 4:

Table 4 – Variables for Formula (5)

Abbreviation	Description	Unit
I_{out}	CDM output current, RMS value according to Table 1	A
ϕ	Phase angle between fundamental CDM output voltage and fundamental CDM output current according to Table 2	°
m	Modulation index, identical to the relative CDM output frequency up to the rated output frequency	

5.2.2.3 Freewheeling diode on state losses

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

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

The RCDM parameters in Formula (6) are given in Table 5:

Table 5 – Reference parameters for Formula (6)

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 (6) are identical to the variables in Formula (5).

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 $I_{\text{motor_cable}}$ 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 6 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:

$$P_{\text{L,sw,T}} = \frac{E_{\text{T}}}{\pi} \cdot U_{\text{DC}} \cdot \sqrt{2} \cdot (I_{\text{out}} + I_{\text{motor_cable}}) \cdot f_{\text{sw}} \quad (7)$$

The RCDM parameters in Formula (7) are given in Table 6:

Table 6 – Reference parameters for Formula (7)

Abbreviation	Description	RCDM parameter value	Unit
E_{T}	Switching loss energy of the power transistor (IGBT) per volt and per ampere	$7,5 \times 10^{-7}$	$\frac{\text{J}}{\text{V} \cdot \text{A}}$
U_{DC}	CDM DC link voltage	540	V
$I_{\text{motor_cable}}$	Motor cable current, relevant for increased switching losses	$I_{\text{motor_cable}} = 4$ for $I_{\text{r,out}} \leq 4$ A $I_{\text{motor_cable}} = i_{\text{r,out}}$ for $4 \text{ A} < I_{\text{r,out}} < 10$ A $I_{\text{motor_cable}} = 10$ for $I_{\text{r,out}} \geq 10$ A	A
f_{sw}	CDM switching frequency	4 000 for a CDM up to 90 kW 2 000 for a CDM above 90 kW	Hz

The variable in Formula (7) 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 0 Hz for all operating time of the CDM, Formula (7) would not be correct anymore. However, it can be assumed that for nearly all applications at least a small output frequency different from 0 Hz, for example 0,05 Hz, will be found, so Formula (7) shall be used for all applications.

5.2.2.5 Freewheeling diode switching losses

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

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

The RCDM parameters in Formula (8) are given in Table 7:

Table 7 – Reference parameters for Formula (8)

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

5.2.2.6 Output inverter total losses

The losses calculated in the Formulae (5) to (8) 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:

$$P_{L, \text{inverter}} = 6 \cdot (P_{L, \text{on}, T} + P_{L, \text{on}, D} + P_{L, \text{sw}, T} + P_{L, \text{sw}, D}) \quad (9)$$

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 part of the converter is the mains input current of the CDM.

The AC side fundamental 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, $\cos \phi$, between fundamental input current and fundamental input voltage is close to 1 in case of motoric 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 $I_{\text{out}} \cdot m \cdot \cos \phi$.

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 (10):

$$P_{L, \text{rectifier}} = 6 \cdot \left(\frac{\sqrt{2}}{\pi} \cdot m \cdot \cos \phi \cdot I_{\text{out}} \cdot U_{D, \text{th}, \text{rectifier}} + \frac{U_{D, \text{r}, \text{rectifier}} - U_{D, \text{th}, \text{rectifier}}}{\cos \phi_r \cdot I_{r, \text{out}}} \cdot \frac{\left(\frac{m \cdot \cos \phi \cdot I_{\text{out}}}{\lambda} \right)^2}{2} \right) \quad (10)$$

The RCDM parameters in Formula (10) are given in Table 8:

Table 8 – Reference parameters for Formula (10)

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 (10) are given in Table 9:

Table 9 – Variables for Formula (10)

Abbreviation	Description	Unit
ϕ_t	Phase angle between fundamental CDM output voltage and fundamental CDM output current at rated torque according to Table 2	°

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

$$P_{L,choke} = k1_{choke} \cdot k2_{choke} \cdot 3 \cdot \frac{\left(\frac{m \cdot \cos \phi \cdot I_{out}}{\lambda} \right)^2}{\cos \phi_t \cdot I_{r,out}} \cdot U_{mL1} \quad (11)$$

The RCDM parameters for the reference converter in Formula (11) are given in Table 10:

Table 10 – Reference parameters for Formula (11):

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 Clause 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:

$$P_{L,dc_link} = k1_{DC_link} \cdot I_{r,out} \cdot U_{DC}^2 + k2_{DC_link} \cdot \frac{\left(\frac{\sqrt{3}}{1,35} \cdot \frac{m \cdot \cos \phi \cdot I_{out}}{1 + 50 \cdot k1_{choke}} \right)^2}{I_{r,out}} \quad (12)$$

The RCDM parameters for the reference converter in Formula (12) are given in Table 11:

Table 11 – Reference parameters for Formula (12)

Abbreviation	Description	RCDM parameter value	Unit
$k1_{DC_link}$	Load independent DC link loss parameter	8×10^{-7}	$\frac{1}{\Omega \cdot A}$
$k2_{DC_link}$	Load dependent DC link loss parameter	2	$\Omega \cdot A$

The determination of the parameters $k1_{DC_link}$ and $k2_{DC_link}$ for a CDM is explained in Clause B.5.

5.2.6 Current conductor losses

Ohmic losses are generated for example in current conductors of the CDM. In the mathematical model, these losses depend on the amplitude of the CDM output current and the ohmic resistance of current conductors. This ohmic resistance reduces in a linear way with increased rated CDM output current, because higher power CDMs use current conductors with a larger diameter. Consequently, the voltage drop at the ohmic conductor elements remains independent of the rated CDM current.

$$P_{L,rails} = \frac{U_{rails}}{I_{r,out}} I_{out}^2 \quad (13)$$

The RCDM parameter for the reference CDM in Formula (13) is given in Table 12:

Table 12 – Reference parameters for Formula (13)

Abbreviation	Description	RCDM parameter value	Unit
U_{rails}	Voltage drop at ohmic conductor elements at rated CDM current	0,7	V

5.2.7 Control and standby losses

In Clause B.10, the load independent losses are explained. In order to get comparable results, these losses shall be evaluated without external components such as position sensors, communication electronics and motor brakes connected. For the reference converter, they shall assumed to be the value in Table 13.

Table 13 – Reference parameter for Formula (15)

Abbreviation	Description	RCDM parameter value	Unit
$P_{L,control}$	Standby and control losses	50	W

5.2.8 Cooling loss factor

State-of-the-art CDMs use a cooling system to transport the losses to the ambient. In many cases, for example a fan is used, which is a part of the CDM. This cooling component causes additional losses. In the mathematical model, these losses are calculated proportional to all other losses created in the CDM at its operating point of maximum losses.

$$P_{L,cooling} = k_{L,cooling} \cdot (P_{L,inverter(90;100)} + P_{L,rectifier(90;100)} + P_{L,rails(90;100)} + P_{L,DC_link(90;100)} + P_{L,choke(90;100)} + P_{L,control}) \quad (14)$$

For the RCDM, the cooling loss parameter is set to 20 % (see Table 14):

Table 14 – Reference parameter for Formula (14)

Abbreviation	Description	RCDM parameter value	Unit
$k_{L,cooling}$	Cooling loss parameter	0,2	

5.2.9 Other CDM losses

All losses in other parts of the CDM are neglected in the mathematical model, as they are significantly lower than the losses described above.

5.2.10 Overall CDM losses

All the losses in the CDM shall be with reference to the rated apparent output power of the PDS, which is formed by the rated output phase voltage and rated output current of the CDM. As a final result of 5.2, the absolute CDM losses result in:

$$P_{L,CDM} = P_{L,inverter} + P_{L,rectifier} + P_{L,choke} + P_{L,rails} + P_{L,DC_link} + P_{L,control} + P_{L,cooling} \quad (15)$$

The relative losses of the CDM result in:

$$P_{L,CDM} = \frac{P_{L,CDM} / kW}{S_{r,eq} / kVA} \quad (16)$$

The following Figure 12 shows the relationship between relative torque producing current, relative motor stator frequency and relative losses $p_{L,CDM,relative}$ of the 9,95 kVA (see Table 18) reference CDM operated at 400V:

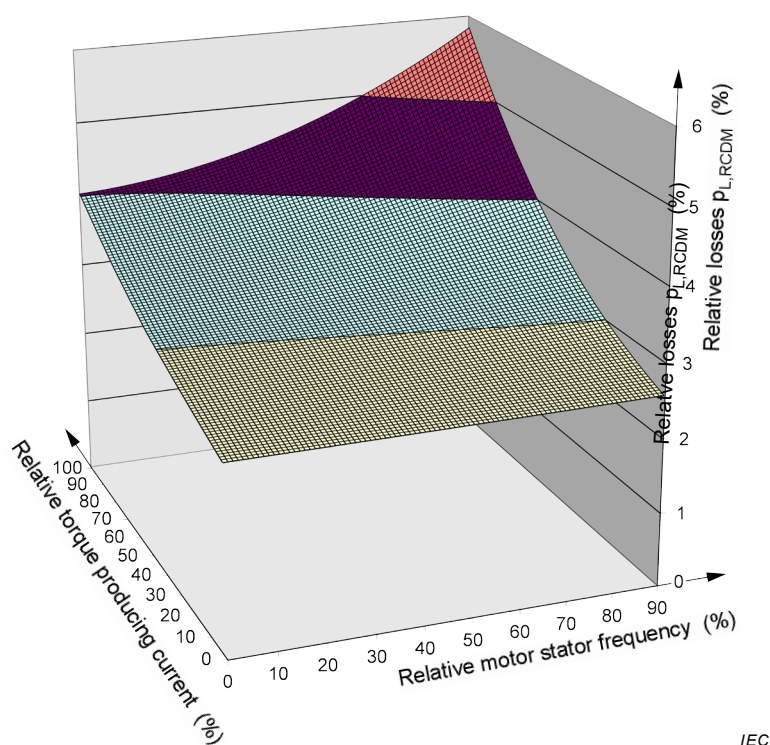


Figure 12 – Relative losses $p_{L,RCDM}$ of the 9,95 kVA RCDM

The following Table 15 shows the relative losses of the 400 V/9,95 kVA reference CDM at the operating points defined in Figure 6:

Table 15 – Relative losses of the 400 V/9,95 kVA reference CDM at the operating points described in Figure 6

$S_{r,eq}$ kVA	I_{rout} A	$p_{L,RCDM}$ (0;25) %	$p_{L,RCDM}$ (0;50) %	$p_{L,RCDM}$ (0;100) %	$p_{L,RCDM}$ (50;25) %	$p_{L,RCDM}$ (50;50) %	$p_{L,RCDM}$ (50;100) %	$p_{L,RCDM}$ (90;50) %	$p_{L,RCDM}$ (90;100) %
9,95	14,4	2,80	3,09	4,02	2,86	3,28	4,64	3,61	5,84

The value of 5,84 % of losses refers to the rated apparent output power of 9,95 kVA, resulting in absolute loss value of 581 W. The relative losses of RCDM's with a different rated power are given for the operating point (90;100) in Table 18 and in Table A.1 for all operating points defined in Figure 6.

5.3 Motor losses

5.3.1 General

Three-phase asynchronous motors are widely used in industrial applications. They are standard products and generally able to run direct on-line or on variable voltage and frequency supplied by a CDM.

In order to determine losses, efficiencies and the efficiency class of a PDS, the user needs information on motor losses. Such information can be obtained either

- from the motor manufacturer, or

- from losses of the reference motor as given in Annex A, or
- from typical losses of standard IE2 machines as given in Annex D.

The interpolation procedure given in Annex D shall be applied to obtain losses and efficiency at any required operating point (load, torque), for example those of 4.2, from the losses provided by the manufacturer at the seven reference points (see Table F.2).

5.3.2 Additional harmonic losses of three-phase asynchronous motors fed by a CDM

Often, losses of three-phase induction motors are only available for on-line operation at purely sinusoidal voltage. When such a motor is operated on a CDM, additional harmonics losses P_{LHL} are caused by the non-sinusoidal voltage supply.

Preferably, the motor should be re-tested on a CDM to determine these losses (see Annex D).

Alternatively, the additional harmonic losses can be determined by using a fixed ratio r_{HL} as an estimation.

r_{HL} represents the ratio of additional harmonic losses of converter supply to losses of the motor supplied with sinusoidal input voltage at nominal power and nominal frequency (see IEC 60034-2-3).

The total losses are:

$$P_{LHL} = r_{HL} \cdot P_{LTsin} \quad (17)$$

where

P_{LTsin} are the total losses determined at sinusoidal power supply at any operating point;

P_{LHL} are the total losses estimated for CDM power supply at that operating point.

Additional harmonic losses due to a converter supply shall be considered constant and independent of load and speed. They are dependent on the switching frequency.

Unless r_{HL} is known from measurements according to IEC 60034-2-3, the following estimations shall be used:

$r_{HL} = 0,15$ (15 %) for motors with a rated output power up to 90 kW and 4 kHz switching frequency

$r_{HL} = 0,25$ (25 %) for motors with a rated output power above 90 kW and 2 kHz switching frequency

5.3.3 Reference motor (RM) data

Reference motor losses are given in Annex A.

The tabled values were derived from the 50 Hz IE2 efficiency values of 4-pole asynchronous machines according to IEC 60034-30-1, from the factor r_{HL} as described in 5.3.2, from the factors K_{fe} , K_{ll} and K_{fw} all set equal to 0,5 as described in Annex D and from a voltage drop correction factor of $400/360 = 1,11$ at rated speed (see Annex D).

The 50 Hz reference motor values shall also be used in 60 Hz applications.

5.4 Reference PDS (RPDS)

5.4.1 Reference PDS losses

The resulting electrical power losses of the PDS at a specific speed (n) and torque (T) operation point will be the sum of the electrical power losses of the subcomponents of the PDS according to Formula (18):

$$P_{L,PDS(n;T)} = P_{L,CDM(n;T)} + P_{L,Aux(n;T)} + P_{L,Mot(n;T)} \quad (18)$$

where

$P_{L,CDM}$ is the losses of the CDM according to methods from 5.2;

$P_{L,Mot}$ is the losses of the motor according to methods from 5.3;

$P_{L,Aux}$ is the losses of the auxiliaries according to Annex B.

A reference PDS (RPDS) is defined to be a single motor (RM) and a single CDM (RCDM). Auxiliaries are not included in the reference PDS.

The selection of matching RM and RCDM for the RPDS is done according to power, see Annex A.

The calculation of losses is generally performed according to Formula (18). However, RPDS losses at 100 % speed and 100 % torque are determined according to Formula (19) by using the 90 % frequency and 100 % torque point of the RCDM and the 100 % speed and 100 % torque point of the motor.

The 90 % frequency of the RCDM is used in order to avoid overmodulation, which would appear for 100 % frequency of the RCDM. Overmodulation decreases the losses of the CDM but increases harmonic motor losses due to higher harmonic contents in the motor's voltages and currents.

The loss calculation of the RPDS is using the assumption that the RCDM losses at the operating point 100 % frequency and 90 % voltage are the same as for the operating point at 90 % frequency and 90 % voltage. It is further assumed that fundamental losses of the RM increase with a correction factor $k_{VD} = 1,11$ (according to 10 % voltage drop – see Clause D.4) compared to Formula (18).

$$P_{L,RPDS(100;100)} = P_{L,RCDM(90;100)} + k_{VD} \cdot P_{L,RM(100;100)} \quad (19)$$

The reference parameter for Formula (19) is given in Table 16.

Table 16 – Reference parameter for Formula (19)

Abbreviation	Description	Value	Unit
k_{VD}	Correction factor of motor losses for the RPDS, see F.3.1.	1,11	

It is in the responsibility of the PDS supplier to add all losses that are part of the PDS, for example motor, CDM, auxiliaries (filter, cable, etc.), for the calculation of losses of an actual PDS.

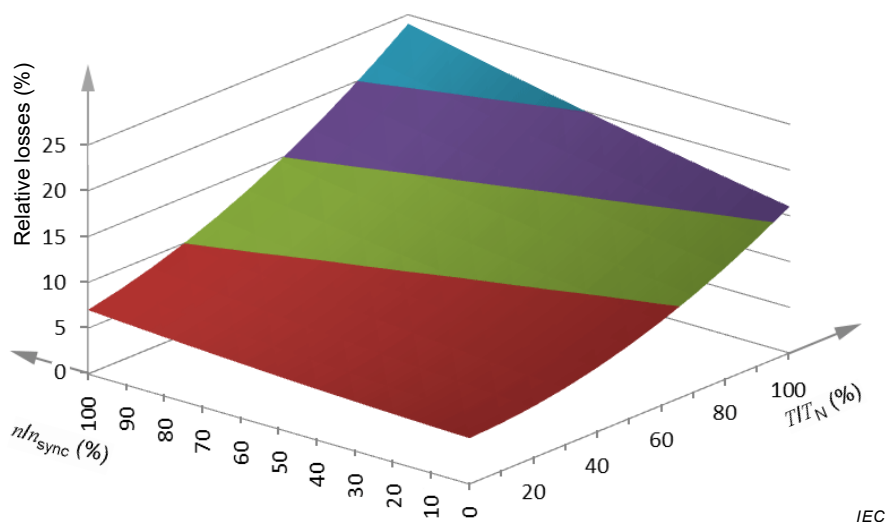
The following Table 17 shows the relative losses of an 400 V/7,5 kW reference PDS (RCDM and RM) at the operating points defined in Figure 6:

Table 17 – Relative losses of the 400 V/7,5 kW RPDS

$P_{r,M}$ kW	$P_{L,RPDS}$, relative (0;25) %	$P_{L,RPDS}$, relative (0;50) %	$P_{L,RPDS}$, relative (0;100) %	$P_{L,RPDS}$, relative (50;25) %	$P_{L,RPDS}$, relative (50;50) %	$P_{L,RPDS}$, relative (50;100) %	$P_{L,RPDS}$, relative (100;50) %	$P_{L,RPDS}$, relative (100;100) %
7,5	6,21	7,80	14,63	7,79	9,65	17,36	13,45	24,01

The relative losses of RPDS with different rated powers are given in Table A.3.

An example for the relative losses is shown in Figure 13. All relative values are related to the rated output power of the PDS.

**Figure 13 – Example of the relative power losses of PDS as function of speed and torque**

5.4.2 PDS losses at different switching frequencies

PDS are often operated with parameters that are different from those used by the RPDS. An important parameter for the loss calculation of the CDM is the switching frequency. An increased switching frequency will increase the losses of the CDM but the additional harmonic losses of the motor will decrease.

The resulting power losses of a PDS for a dedicated switching frequency will be the sum of the electrical power losses of the subcomponents of the PDS, see Formula (20) and example in figure 12, when the operating point (speed, torque) is kept constant.

$$P_{L,PDS}(f_{sw}) = P_{L,CDM}(f_{sw}) + P_{L,Aux}(f_{sw}) + P_{L,Mot}(f_{sw}) \quad (20)$$

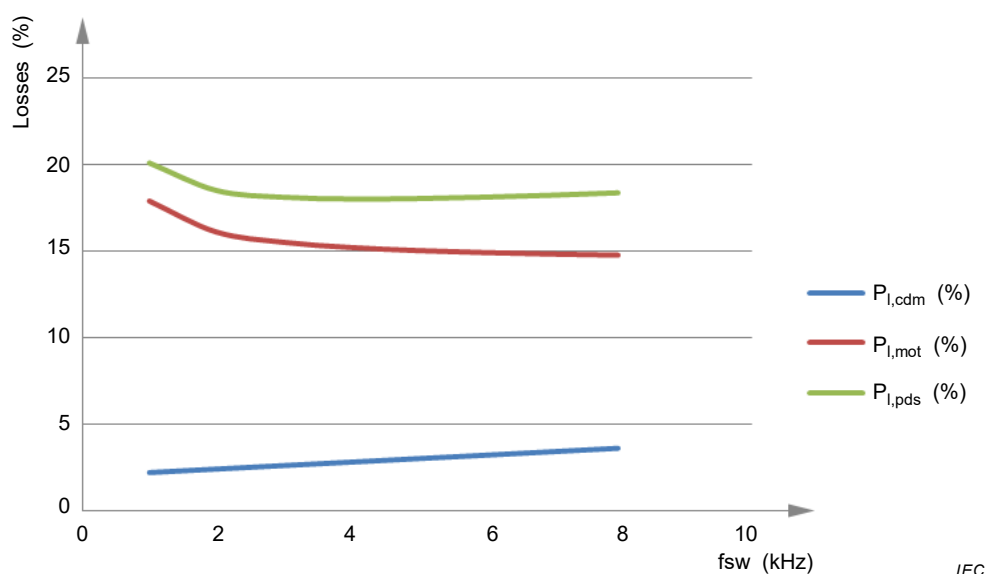


Figure 14 – Example of the relative power losses versus switching frequency

5.5 PDS losses for regenerative operation

Some PDSs have the capability of handling regenerative loads, i.e. loads that generate electrical power. Power can be generated from decelerating the inertia of a load or motor, or from torque produced by the load (for example by draft in a fan).

Some CDMs have the capability to feed the generated power into the mains by using an active infeed converter (AIC). The power fed into the mains is the generated power minus the losses of the PDS.

A CDM can also have the capability to dissipate the generated power into heat, which is distributed inside or outside of the CDM (for example by a resistor), see Figure 14. The power dissipated in the resistor is considered as auxiliary losses for the PDS loss calculation, see Formula (18).

A CDM can also have the capability to store electrical energy in batteries, capacitors or similar technologies. This energy can later be reused when active motor power is needed. Such storage devices cause losses that have to be added as auxiliary losses when calculating the losses of the extended product.

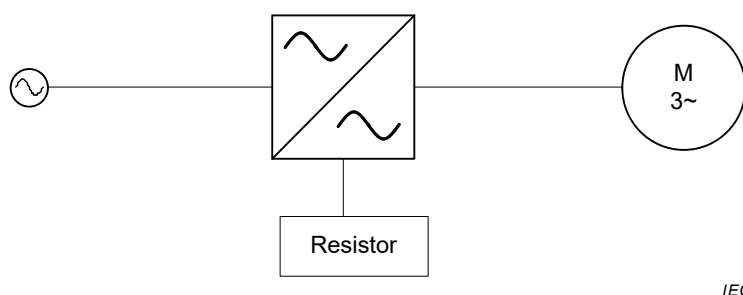


Figure 15 – Example of a CDM with resistor for dissipating generated power

5.6 Losses of motor starters

For the purpose of loss calculations, the power losses of motor starters (including control losses) according to the product standard IEC 60947-4-1 shall be calculated as 0,1 % of the rated motor power.

Soft starters according to the product standard IEC 60947-4-2 are usually mechanically bypassed at longer duty cycle (S1 operation) and therefore calculated like motor starters.

The power losses of motor starters are sufficiently small so that the same IE class is used for a motor as well as for a motor controlled by a starter.

6 Limits of IE and IES classes

6.1 General

The losses or efficiency of the reference CDM, reference motor and reference PDS are used as a basis for assessing compliance with an IE and IES class of an existing motor, CDM or PDS.

Reference devices are associated with IE1 and IES1. Existing devices with losses lower than the reference losses (i.e. better efficiency) are identified by levels higher than 1. The threshold and tolerance of each level are specified in 6.2 to 6.4.

Compliance with an IE and IES class can be shown by either measurements or by calculations, which are described in Clause 7. The various test points shown in Figure 4 can be used to determine the losses and energy efficiency of an overall system for a specific application.

In order to minimize the certification process, compliance with an IE class shall be shown for the CDM at rated current and 90 % rated motor stator frequency, respectively rated motor voltage, only.

Compliance with an IES class shall be shown for the PDS at rated torque and rated shaft speed only.

Regenerative operation is not taken into account when determining an IE or IES class for a CDM or a PDS.

NOTE The rated output current of a CDM is its maximum steady-state output current.

6.2 CDM

The reference CDM is described by the parameters given in 5.2. Its losses are given in Table 18.

The power rating of a RCDM is defined according to its apparent output power, which is of most influence on CDM losses.

As CDMs are usually rated according to output current rather than apparent output power, examples of rated RCDM output currents are given in Table 18 for typical standard line voltages. The relation to standard motor power ratings defined in IEC 60072-1 and IEC 60034-30-1 can be found in Table A.1.

Table 18 – Reference CDM losses for class IE1 definition

Apparent output power $S_{r, \text{equ}}$	Relative losses $p_{L, \text{RCDM}} (90, 100)$	Absolute losses $P_{L, \text{RCDM}} (90, 100)$	Examples for CDM output current at typical line voltages $I_{r, \text{out}} = \frac{S_{r, \text{equ}}}{\sqrt{3} \cdot U_{1, r, \text{out}}}$			
kVA	%	kW	$U_{1, r, \text{out}} = 200\text{V}$	$U_{1, r, \text{out}} = 400\text{V}$	$U_{1, r, \text{out}} = 460\text{V}$	$U_{1, r, \text{out}} = 690\text{V}$
			A			
0,278	35,85	0,100	0,803	0,401	0,349	0,233
0,381	27,30	0,104	1,10	0,550	0,478	0,319
0,500	21,80	0,109	1,44	0,722	0,627	0,418
0,697	16,84	0,117	2,01	1,01	0,875	0,583
0,977	13,21	0,129	2,82	1,41	1,23	0,818
1,29	11,02	0,142	3,73	1,86	1,62	1,08
1,71	9,51	0,163	4,94	2,47	2,15	1,43
2,29	8,21	0,188	6,62	3,31	2,88	1,92
3,30	7,20	0,237	9,54	4,77	4,15	2,76
4,44	6,72	0,299	12,8	6,41	5,58	3,72
5,85	6,39	0,374	16,9	8,44	7,34	4,89
7,94	6,01	0,477	22,9	11,5	9,96	6,64
9,95	5,84	0,581	28,7	14,4	12,5	8,32
14,4	5,43	0,781	41,6	20,8	18,1	12,1
19,5	5,18	1,01	56,2	28,1	24,4	16,3
23,9	5,05	1,21	68,9	34,4	30,0	20,0
28,3	4,97	1,41	81,6	40,8	35,5	23,6
38,2	4,87	1,86	110	55,2	48,0	32,0
47,0	4,79	2,25	136	67,8	58,9	39,3
56,9	4,75	2,70	164	82,1	71,4	47,6
68,4	4,74	3,24	197	98,7	85,8	57,2
92,8	4,69	4,35	268	134	116	77,6
111	4,66	5,17	321	160	139	93,0
135	4,11	5,55	391	195	170	113
162	4,10	6,65	468	234	203	136
196	4,09	8,02	566	283	246	164
245	4,07	10,0	706	353	307	205
302	4,10	12,4	872	436	379	253
381	4,09	15,6	1 099	550	478	319
429	4,09	17,5	1 239	619	539	359
483	4,09	19,8	1 396	698	607	405
604	4,08	24,7	1 745	872	758	506
677	4,08	27,6	1 954	977	850	566
761	4,08	31,1	2 198	1 099	956	637
858	4,08	35,0	2 477	1 239	1 077	718
967	4,08	39,4	2 791	1 396	1 214	809
1 088	4,08	44,3	3 140	1 570	1 365	910
1 209	4,08	49,3	3 489	1 745	1 517	1 011

NOTE 1 The change of the switching frequency from 4 kHz at 111 kVA to 2 kHz at 135 kVA causes a discontinuity in the relative RCDM loss values $p_{L, \text{RCDM}}$ between those power ratings.

If the rated apparent output power of a CDM is between two values in Table 18, the relative loss value $p_{L,RCDM}$ of the RCDM with the next higher power rating shall be used for the IE class determination. The RCDM losses in Table 18 shall be used for all low voltage (above 200 V up and equal to 1 000 V) CDMs. For a given apparent output power rating, CDMs with an input voltage up to and including 200V are expected to create higher losses than CDMs rated for higher input voltage. In order to take this into account, the values in Table 18 shall be multiplied by a factor of 1,35 (reference IEC TS 61800-8) when assessing the IE class for a CDM with a rated input voltage up to 200 V.

A CDM shall be classified as IE1 if its relative losses are within ± 25 % of the RCDM value.

A CDM shall be classified as IE0 if its relative losses are more than 25 % higher than the RCDM value.

A CDM shall be classified as IE2 if its relative losses are more than 25 % lower than the RCDM value.

These definitions are illustrated in Figure 16:

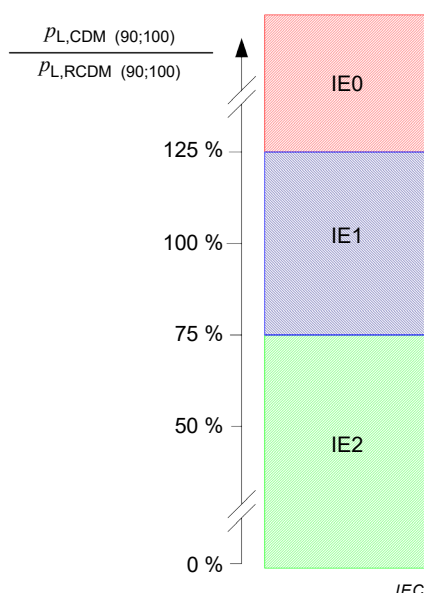


Figure 16 – Illustration of IE classes for a CDM

NOTE 2 In this document, limit classes for CDMs are defined up to IE2 only. Classes IE 3 up to IE 9 are reserved to describe future technological improvements of CDMs.

In this document, the determination of IE classes is only mandatory for CDMs converting AC input power to AC output power.

6.3 Motor

IE classes for motors operated on a CDM are defined in IEC 60034-30 (all parts).

6.4 PDS

The IES classes of PDS system are defined in relation to RPDS losses. The IES1 class of PDS is defined by the loss level of the RPDS.

A PDS shall be classified as IES1 if its relative losses are within ± 20 % of the value specified in Table 19.