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BSI Standards Publication

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.

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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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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CENELEC

European Committee for Electrotechnical Standardization
Comité Européen de Normalisation Electrotechnique
Europäisches Komitee für Elektrotechnische Normung

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

Ref. No. EN 50598-2:2014 E

Contents

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• latest date by which the national standards conflicting with this document have to be withdrawn	(dow)	2017-11-17

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.

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.

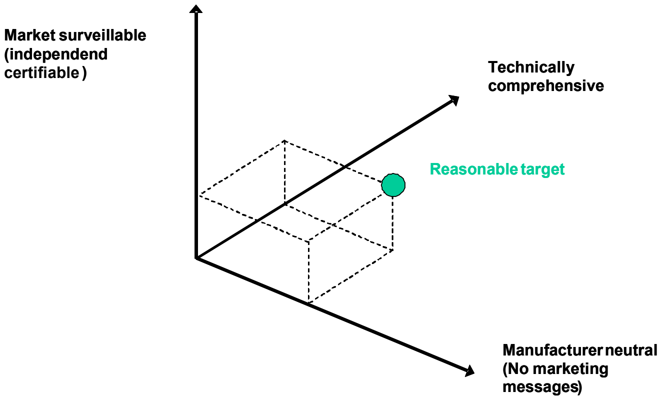


Figure 1 — Illustration of controversial requirements for the energy related product (ErP) standardization

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 indiviual 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
EEI

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.

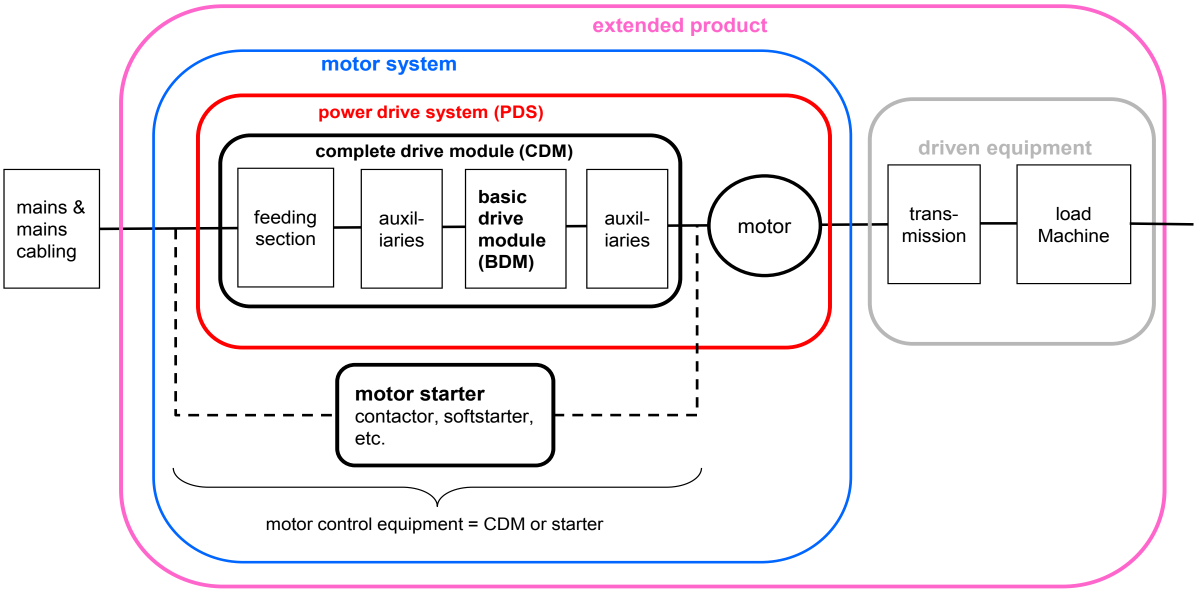


Figure 2 — Illustration of the extended product with included motor system

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

$I_{\mathrm{motor\_cable}}$

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

3.2.6

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

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

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

rated CDM output current

3.2.10

I_{rM}

rated motor current

3.2.11

$k1_{\mathrm{DC\_link}}$

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

3.2.12

$k1_{\text{choke}}$

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

$P_{\mathrm{L,choke}}$

power losses in the choke section of a CDM

3.2.40

$P_{\mathrm{L,control}}$

power losses in the control section of a CDM

3.2.41

$P_{\mathrm{L,DC\_link}}$

power losses of the DC link section of the CDM

3.2.42

$P_{\mathrm{L,inverter}}$

power losses in the inverter section of a CDM

3.2.43

$P_{\mathrm{L,PDS,\ determined}}$

power losses of PDS from the power loss determination method

3.2.44

$P_{\mathrm{L,rectifier}}$

power losses in the rectifier section of a CDM

3.2.45

$P_{\mathrm{L,resistor}}$

measured power losses of the resistor in comparative calorimetric measurement

3.2.46

$P_{\mathrm{L,on,D}}$

on state power losses of a power diode

3.2.47

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

on state power losses of a rectifier diode

3.2.48

$P_{\mathrm{L,on,T}}$

on state losses of a power transistor

3.2.49

$P_{\mathrm{L,sw,D}}$

switching power losses of a power diode

3.2.50

$P_{\mathrm{L,sw,T}}$

switching power losses of a power transistor

3.2.51

$P_{\mathrm{r,M}}$

rated power of a motor

Note 1 to entry: In the motor standard series EN 50034 this is named P_{N}.

3.2.52

$P_{\mathrm{L,\ stby}}$

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

3.2.58
$S_{\mathrm{r,RCDM}}$
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
$U_{\mathrm{1,r,out}}$
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
$U_{\mathrm{D,r}}$
on state voltage of a power diode at rated CDM current

3.2.65
$U_{\mathrm{D,r,rectifier}}$
on state voltage of a rectifier diode at rated CDM current

3.2.66
$U_{\mathrm{D,th}}$
threshold voltage of a power diode

3.2.67
$U_{\mathrm{D,th,rectifier}}$
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
$U_{\mathrm{T,r}}$
on state voltage of a power transistor at rated CDM current

3.2.70
$U_{\mathrm{T,th}}$
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: $\lambda = P_{\mathrm{equ}}/S_{\mathrm{r,equ}}$

3.2.73
$\Delta p_{\mathrm{L,CDM}}$

uncertainty [%] of power loss determination method for CDM

3.2.74
$\Delta P_{\mathrm{L,CDM}}$
uncertainty [W] of power loss determination method for CDM

3.2.75
$\Delta p_{\mathrm{L,PDS}}$
uncertainty [%] of power loss determination method for PDS

3.2.76
$\Delta P_{\mathrm{L,PDS}}$
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 called "square torque loads" will typically require the relative losses or the input powers P_1 of the points $p_{\text{L, PDS (50; 25)}}$, $p_{\text{L, PDS (100; 50)}}$ and $p_{\text{L, PDS (100; 100)}}$ in order to calculate the losses of the embedded Motor system. The permissible loss tolerances is ± 10 % of the losses in each operating point.
>
> Hoisting equipment or other so called "constant torque loads" will additionally need the points $p_{\text{L, PDS (0; 25)}}$, $p_{\text{L, PDS (0; 50)}}$ and $p_{\text{L, PDS (0; 100)}}$ 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) wich 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.

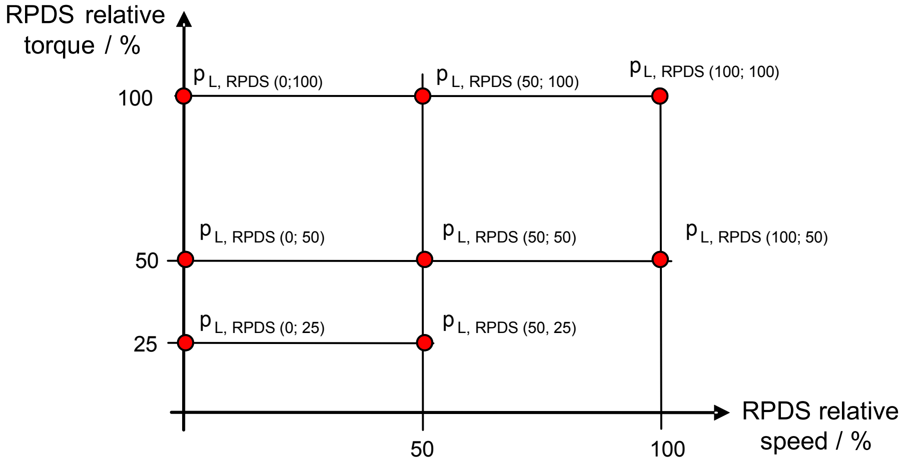


Figure 3 — Illustration of the operating points for speed versus torque to determine the relative power losses of the power drive system (RPDS)

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:

$$P_{L,RPDS} = P_{L,RM} + P_{L,RCDM} \tag{1}$$

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

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

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

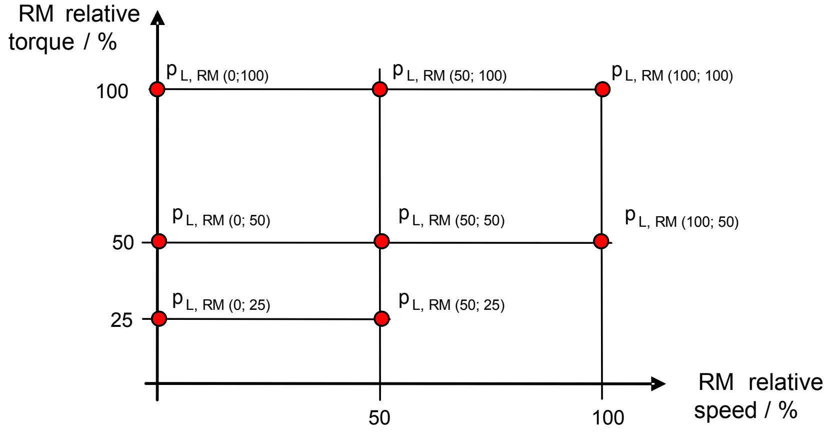


Figure 4 — Illustration of the operating points for speed versus torque to determine the relative power losses of the reference motor (RM)

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.

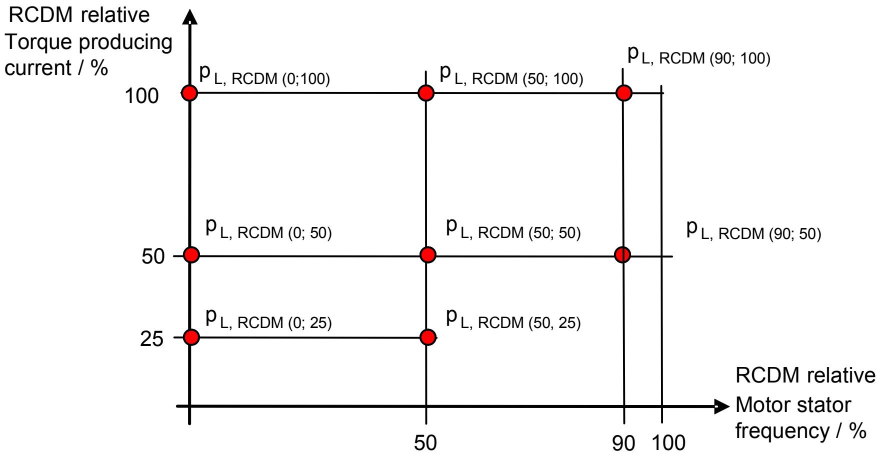


Figure 5 — Illustration of the operating points of the RCDM depending on the relative torque-producing current and the relative motor stator frequency, to determine the losses of reference complete drive module (RCDM)

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.

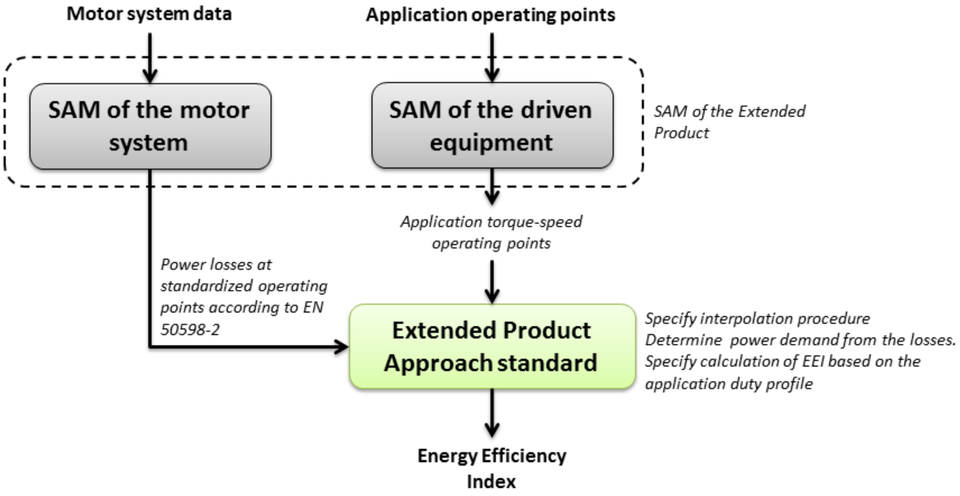


Figure 6 — Illustration of the workflow to determine the energy efficiency index (EEI) of an extended product

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.

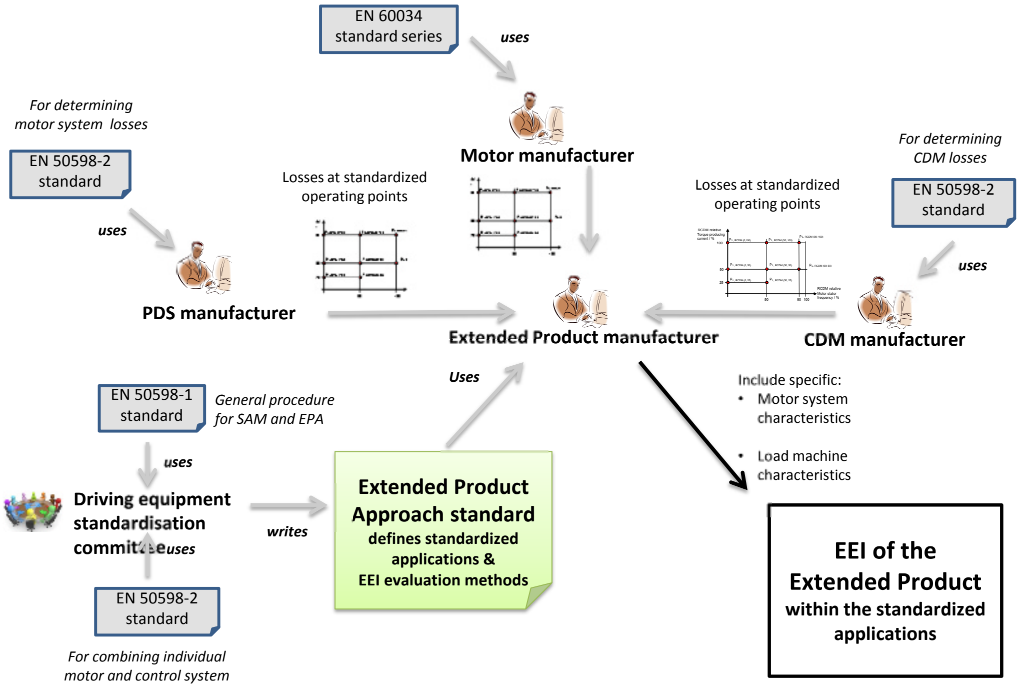


Figure 7 — Illustration how to combine different data sources to determine the energy efficiency index (EEI) of an extended product

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.

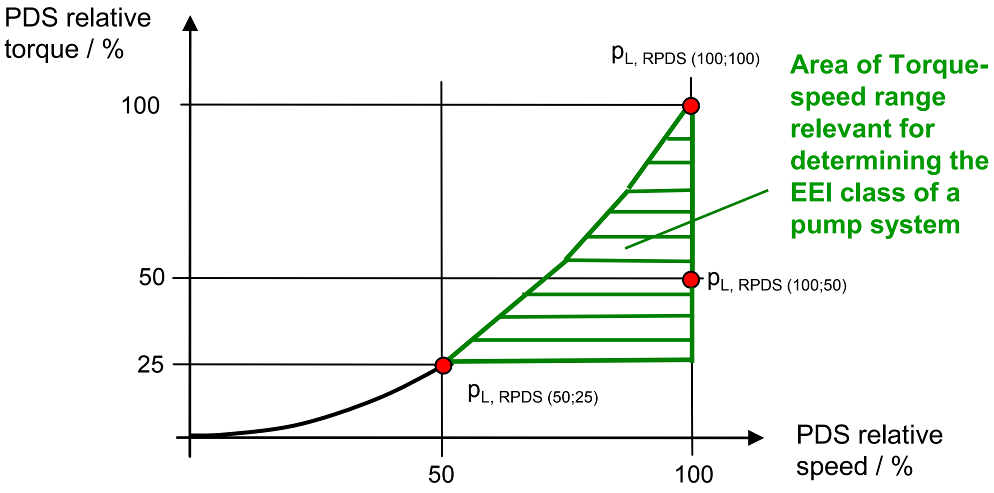


Figure 8 — Three points of relative losses and shaded area of interest for the pump manufactures while defining the EEI (Energy Efficiency Index) of a pump unit

Providing the electrical power losses of the three points $p_{\mathrm{L,PDS(50;\ 25)}}$, $p_{\mathrm{L,PDS(100;\ 50)}}$ and $p_{\mathrm{L,PDS(100;\ 100)}}$ 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 ± 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.

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

($P_{\mathrm{L,CDM}}$ + $P_{\mathrm{L,\ Aux}}$) 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 ±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.

$P_{\mathrm{L,Mot}}$ 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}=4kHz (rated power up to 90 kW) or f_{sw} =2 kHz (rated powers above 90 kW).

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

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.

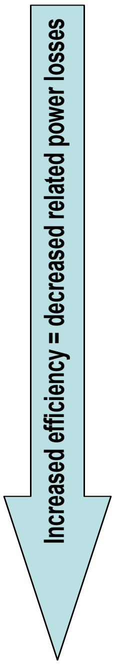
The so called "Reference PDS (RPDS)", see Figure 3, shall be classified as class IES1.

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 ±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.

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

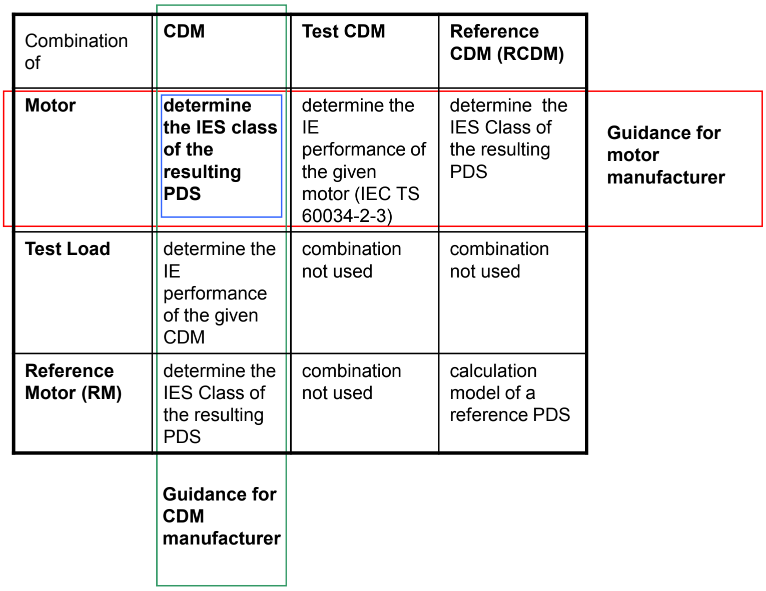
A motor manufacturer may determine the losses of his motor and define an IE class according to Figure 9. He may also define an IES class for a PDS using his motor. For this he shall determine the relative losses for his motor together with a RCDM.

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
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 motor manufacturer

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

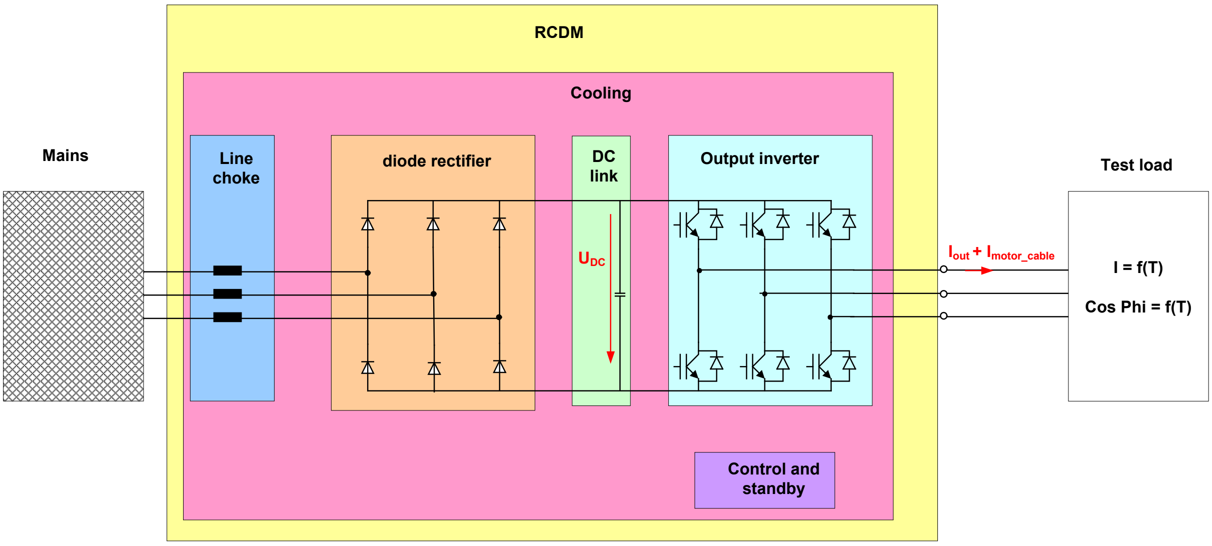


Figure 11 — Illustration of the CDM and the test load

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 $S_{\mathrm{r,equ}}$ 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 ϕ for the apparent power range $S_{\mathrm{r,equ}}$ 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 $P_{\mathrm{r,M}}$, 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:

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

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

$$S_{r,equ} = \sqrt{3} \cdot U_{1,r,out} \cdot I_{r,out} = \frac{P_{r,M}}{\cos\Phi \cdot \eta_{nMotor}} \tag{5}$$

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:

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

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:

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

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 $I_{\text{motor\_cable}}$ 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 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:

$$P_{L,sw,T} = \frac{E_T}{\pi} \cdot U_{DC} \cdot \sqrt{2} \cdot \left(I_{out} + I_{motor\_cable}\right) \cdot f_{sw} \tag{8}$$

The RCDM parameters in Formula (8) are:

Table 7 — Reference parameters for Formula (8)

Abbreviation	Description	RCDM parameter value	Unit
$\boldsymbol{E_T}$	Switching loss energy of the power transistor (IGBT) per volt and per ampere	$7{,}5*10^{-7}$	$\frac{\boldsymbol{J}}{\boldsymbol{V \cdot A}}$
$\boldsymbol{U_{DC}}$	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
$\boldsymbol{f_{sw}}$	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:

$$P_{L,sw,D} = \frac{E_D}{\pi} \cdot U_{DC} \cdot \sqrt{2} \cdot \left(I_{out} + I_{motor\_cable}\right) \cdot f_{sw} \qquad (9)$$

The RCDM parameters in Formula (9) are:

Table 8 — Reference parameters for Formula (9)

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

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:

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

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/λ. 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):

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

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 $k1_{\text{choke}}$ of the rated inverter impedance $U_{\text{mL1}}/I_{\text{equ}}$. Assuming the voltage drop at the resistive part of the input choke to be a certain part $k2_{\text{choke}}$ of the overall voltage drop on the input choke, the losses in the input choke shall be calculated to

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

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:

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

The RCDM parameters for the reference converter in Formula (13) are:

Table 12 — Reference parameters for Formula (13)

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	0,5	$\Omega \cdot A$

The determination of the parameters $k1_{\text{DC\_link}}$ and $k2_{\text{DC\_link}}$ for a CDM is explained in B.5.

5.2.6 Current conductor losses

Ohmic losses are generated e.g. 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 CDM's use current conductors with a larger diameter. Consequently, the voltage drop at the ohmic conductor elements remains independent of the rated CDM current.

$$P_{L,rails} = \frac{U_{rails}}{I_{r,out}} \cdot I_{out}{}^{2} \tag{14}$$

The RCDM parameter for the reference CDM in Formula (14) is:

Table 13 — Reference parameters for Formula (14)

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 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 be assumed to be:

Table 14 — Reference parameter for Formula (17)

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, e.g. 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.

$$P_{L,cooling} = k_{L,cooling} \cdot (P_{L,inverter(90;100)} + P_{L,rectifier(90;100)} + P_{L,rails(90;100)} + P_{L,DC\_link(90;100)} \\ + P_{L,choke(90;100)} + P_{L,control}) \quad (15)$$

For the RCDM, the cooling loss parameter is set to 20 %:

Table 15 — Reference parameter for Formula (15)

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 referred 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 this section, the absolute CDM losses result in:

$$P_{L,CDM} = P_{L,inverter} + P_{L,rectifier} + P_{L,choke} + P_{L,rails} + P_{L,DC\_link} + P_{L,control} + P_{L,cooling} \quad (16)$$

The relative losses of the CDM result in:

$$p_{L,CDM} = \frac{\frac{P_{L,CDM}}{W}}{\frac{S_{r,equ}}{VA}} \quad (17)$$

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 20) reference CDM operated at 400 V:

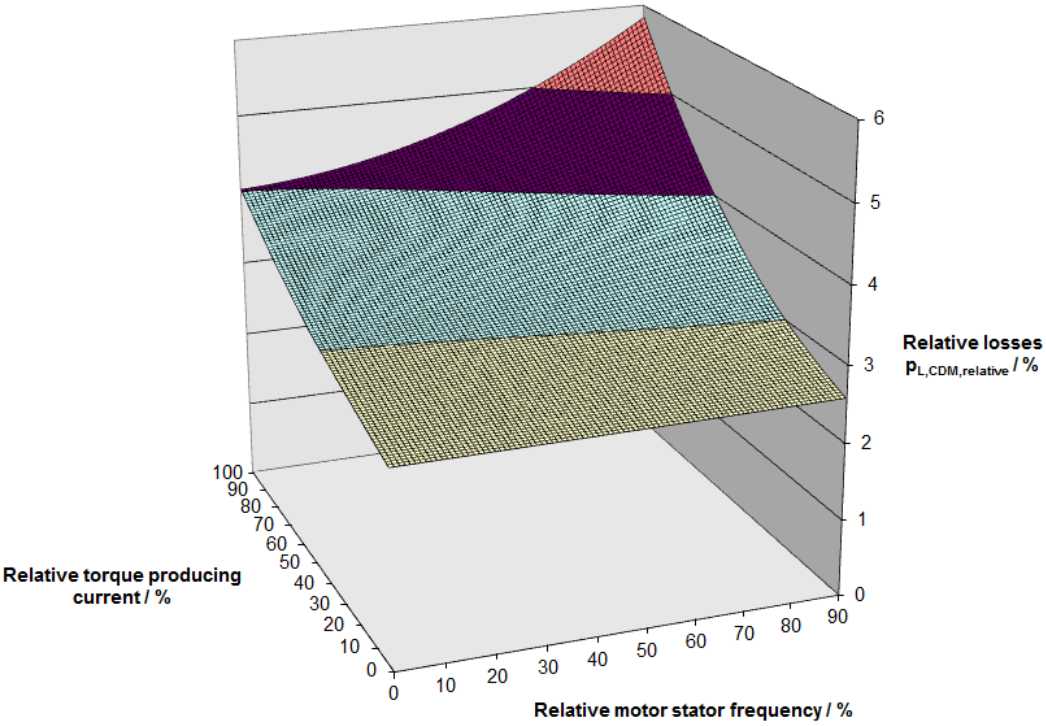


Figure 12 — Relative losses $p_{L,CDM}$ of the 9,95kVA RCDM

The following Table 16 shows the relative losses of the 400V/9,95kVA reference CDM at the operating points defined in Figure 5:

Table 16 — Relative losses of the 400V/9,95kVA reference CDM at the operating points described in Figure 5

P_{rM} / kW	$S_{r,equ}$ /kVA	$p_{L,RCDM}$ (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) /%
7,5	9,95	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 9,95kVA, resulting in absolute loss value of 581W. The relative losses of RCDM's with a different rated power are given for the operating point (90;100) in Table 20 and in Annex A ,Table A.1 for all operating points defined in Figure 5.

5.3 Reference motor (RM)

5.3.1 General

Standard 3-phase asynchronous motors (according to EN 50347) are widely used in industrial applications. These motors are able to run direct on line or to be fed by a CDM. There is no fixed relation between motor and CDM. Available standard products for both can be used.

In order to determine losses or efficiency classes of a complete system, the CDM user needs data from the motor manufacturer or reference values as given in 5.3.3 as well as in Annex A.

The following 5.3.2 only considers the losses of converter-fed 3-phase asynchronous motors. Other motor systems (see e.g. Annex E) will be considered in future editions of this standard.

5.3.2 Loss determination for 3-phase asynchronous motors fed by a CDM

5.3.2.1 General

The formulae in this clause can be used for each 3-phase asynchronous motor. The parameters to be used for the reference motor (RM) are given in 5.3.3.

Efficiency classes for sinusoidal fed asynchronous induction machines are defined in EN 60034-30-1. The classification is done for rated output (P_n: 100 % torque, n_n100 % speed).

The motor losses P_{LT} for this point can be calculated by:

$$P_{LT\sin} = \frac{P_{r,M}}{\eta} - P_{r,M} \tag{18}$$

$P_{r,M}$ and η can be taken from the motor nameplate or if not available for the application, from the tables in EN 60034-30-1 as a reference for a certain motor output power and efficiency class (compare Table 17).

Used in a variable speed drive, it will not be sufficient to know the motor losses only at rated output but also for other points within the speed range of PDS application. In the following it is described, how to get values for the losses depending on torque (load) and speed (frequency) for asynchronous motors.

The formulae developed below are valid as long as the motor is operated in the constant flux region, usually up to the rated speed of the motor.

Especially for smaller motors it is necessary to increase the ratio U/f to get still nominal flux to compensate the resistance of stator winding when standard converters are used.

The efficiency test for asynchronous motors according to EN 60034-2-1:2007, 6.4.4.2 according to method segregated losses requires testing at load points 25 %, 50 %,75 % and 100 % of nominal torque under rated conditions. Instead of measured values also calculated ones i.e. from simulations programs may be used.

For the dependency on frequency (speed) of these loss components, the following applies:

5.3.2.2 Stator winding losses P_{LS}

Tested value according to EN 60034-2-1, independent of frequency (constant flux), only depending on torque (load).

5.3.2.3 Rotor winding losses P_{LR}

Tested value according to EN 60034-2-1, independent of frequency (constant flux), only depending on torque (load).

The absolute value of the nominal slip is considered to be constant over the whole speed-(frequency)-range. It is assumed that the temperature rise of the motor is constant and close to the temperature rise at rated power, -speed and -torque under sinus supply.

5.3.2.4 Iron losses P_{Lfe}

They are determined according to EN 60034-2-1 at nominal frequency and could be separated into two parts:

a) Eddy current losses: $P_{Lfe} * K_{fe}$, in which K_{fe} is the fraction part for eddy current losses. They are proportional to square of frequency.

   If no other value (from test or experience) is available, K_{fe}=0,5 (50 % of measured iron losses) is recommended.

b) Hysteresis losses: $P_{Lfe} * (1-K_{fe})$, which are proportional to frequency.

The total iron losses can be calculated in function of speed (frequency) as follows:

$$P_{Lfe}(f) = P_{Lfe}(f_n) \cdot \frac{f}{f_n} \cdot [(1-K_{fe}) + \frac{f}{f_n} \cdot K_{fe}] \tag{19}$$

f_n is the nominal frequency

5.3.2.5 Additional load losses P_{LL}

They are determined according to EN 60034-2-1:2007, 8.2.2.5.1.3 at nominal frequency and for each load. They can be separated into two parts:

a) Part 1 : $P_{LL} * K_{LL}$, in which K_{LL} is the fraction part of additional load losses which are proportional to square of frequency.

   If no other value (from test or experience) is available, K_{LL}=0,5 (50 % of measured additional load losses) is recommended.

b) Part 2 : $P_{LL} * (1-K_{LL})$ which are proportional to frequency.

The total additional load losses can be calculated in function of speed (frequency) as follows :

$$P_{LL}(f) = P_{LL}(f_n) \cdot \frac{f}{f_n} \cdot \left[(1-K_{LL}) + \frac{f}{f_n} . K_{LL} \right] \tag{20}$$

f_n is the nominal frequency.

5.3.2.6 Friction and windage losses P_{Lfw}

5.3.2.6.1 Self-ventilated motors : IC 411 (EN 60034-6)

They are determined according to EN 60034-2-1 at nominal synchronous speed and could be separated into two parts:

a) Windage (fan): P_{Lfw} * K_{fw} , in which K_{fw} is the fraction part for the windage losses. They are proportional to cube of the speed (frequency).

b) Friction (bearings): P_{Lfw} * *(1-K_{fw})* which are proportional to speed (frequency).

If no other value (from test or experience) is available, the values in the following table for K_{fw} are recommended :

Number of poles	K_{fw}	$1-K_{fw}$	Unit
2	0,7	0,3	without
4	0,5	0,5	without
6	0,3	0,7	without

The total mechanical losses can be calculated in function of speed (frequency) as

$$P_{Lfw}(f) = P_{Lfw}(f_n).\cdot\frac{f}{f_n}\cdot[(1-K_{fw})+\left(\frac{f}{f_n}\right)^2.K_{fw}] \tag{21}$$

f_n is the nominal frequency

5.3.2.6.2 Motors equipped with auxiliary fan: IC 416 (EN 60034-6)

The losses for the auxiliary fan consist of the losses of the auxiliary fan motor and the power the fan needs itself. The sum of both is the input power of the auxiliary fan motor. If this value is not known, it can be calculated by:

$$P_{1\_auxiliary\_fan\_motor} = \frac{P_{n\_auxiliary\_fan\_motor}}{\eta_{auxiliary\_fan\_motor}} \tag{22}$$

1) Losses due to the auxiliary fan are constant and not depending on speed (frequency)

2) Friction losses due to the main motor bearings $\boldsymbol{P_{Lfw}}$ are proportional to speed (frequency)

The total mechanical losses of the main motor including the auxiliary fan can be calculated in function of speed (frequency) as

$$P_{Lfw} = P_{Lfw}(f_n)\cdot\frac{f}{f_n} + P_{1\_auxilary\_fan\_motor} \tag{23}$$

f_n is the nominal frequency

5.3.2.7 Additional harmonic losses P_{LHL}

Additional harmonics losses are caused by non sinusoidal power supply and can be determined by one of the following methods :

Procedure a):

P_{LHL} are determined according to IEC/TS 60034-2-3 methods 2-3-A , 2-3-B or 2-3-C.

Procedure b):

Using the ratio r_{HL} :

> r_{HL} represents additional harmonic losses due to converter supply compared to the losses of the motor supplied with sinusoidal input voltage at nominal power and nominal frequency (compare IEC/TS 60034-2-3)
>
> r_{HL} has been determined from representative tests selected by CLC/TC 22X/WG 06/. Tests of motors have been done at different frequencies and different load under constant nominal flux.
>
> Results of that tests show: The additional harmonic losses due to converter supply may be considered as constant and independent of load, speed and switching frequency provided that the switching frequency is at least 2 kHz.
>
> Additional harmonic losses due to converter supply in the reference motor will be calculated by using the formula:
>
> $$P_{LHL} = r_{HL} \cdot P_{LT\sin} \tag{24}$$
>
> where
>
> P_{LT} are the total losses as defined in Formula (18)
>
> r_{HL}=0,15 (15 %) for motors with a rated output power up to 90 kW
>
> r_{HL} = 0,25 (25 %) for motors with a rated output power above 90 kW.

5.3.2.8 Total losses as function of speed (frequency) and load (torque)

The total motor losses can be calculated for each speed (frequency) and load (torque) as follows:

$$P_{LT,Mot}(f,T) = \left[P_{LS}(T) + P_{LR}(T) + P_{Lfe}(f) + P_{Lfw}(f) + P_{LL}(f,T)\right]_{Sinus\ \sup ply} + P_{LHL} \tag{25}$$

> This formula is based on a motor running at ambient defined on the name plate. In case of harmonic losses determined according to 5.3.2.7, Method a), they might depend on the load.
>
> The formula requires the values of losses according to EN 60034-2-1 at nominal frequency and sinusoidal supply for 25 %, 50 %, 75 % and 100 % load

NOTE 1 These values may be available with the complete test report according to EN 60034-2-1, otherwise refer to Annex F.

NOTE 2 This basic formula can be used without any limitation for pump and fan applications along the speed range.

NOTE 3 For specific applications, e.g. constant torque, it is essential to consider the load capacity of the motor requested during the selection.

NOTE 4 Recommendation for possible torque on the motor shaft between 0 % and 20 % of synchronous speed is 40 % nominal torque for self-ventilated motors (IC 411).

NOTE 5 Annex F developed in this standard gives complementary information to calculate losses versus speed or torque for different motor sizes, with 2 pole and 4 pole by using the formula above.

5.3.3 Data of the reference motor (RM)

The losses for the reference motor are derived from 4 pole asynchronous motors, using the 50 Hz-IE2 efficiency values according to EN 60034-30-1 and the factors r_{HL} as described in 5.3.2.7.

The losses of these reference motors are also valid for 60 Hz applications.

Table 17 — Reference motor losses

P_N / kW	$p_{L,RM\ (100,100)}$ / % of P_N	$P_{L,RM\ (100,100)}$ / W
0,12	79,6	96
0,18	62,7	113
0,25	52,9	132
0,37	43,2	160
0,55	34,2	188
0,75	29,5	221
1,1	26,3	289
1,5	23,9	358
2,2	21,4	471
3	19,5	585
4	17,8	712
5,5	16,1	887
7,5	14,7	1099
11	13,1	1437
15	11,9	1790
18,5	11,1	2053
22	10,5	2320
30	9,6	2878
37	9,1	3351
45	8,5	3835
55	8,0	4397
75	7,3	5505
90	7,1	6373
110	7,3	8003
132	7,0	9234
160	6,7	10748
200	6,4	12881
250	6,4	16101
315	6,4	20288
355	6,4	22864
400	6,4	25762
500	6,4	32203
560	6,4	36067
630	6,4	40576
710	6,4	45728
800	6,4	51525
900	6,4	57965
1000	6,4	64406

NOTE The factor for the additional losses in the motor due to converter fed operation changes according to 5.3.2.7 from 15 % to 25 % between the output powers of 90 kW and 110 kW. This causes a discontinuity in the tabular values.

The values in Table 17 correspond with the values of the apparent power of Table 20 (second column).

In addition to Table 17, Table A.2 in Annex A gives the losses of the reference motors for all 8 points according to Figure 4 using the calculations described in 5.3.2. The parameters of the reference motor for these calculations are given in the following table:

Abbreviation	Description	RM parameter value	Unit	Formula
K_{fe}	fraction part of iron losses, which are eddy current losses	0,5	without	(19)
K_{LL}	fraction part of additional load losses, which are proportional to square of frequency	0,5	without	(20)
K_{fw}	fraction part of the friction and windage losses, which are windage losses	0,5	without	(21)
r_{HL}	ratio of harmonic voltage losses relative to sinusoidal voltage losses	0,15 motors with rated output power up to 90kW 0,25 motors with rated output power above 90kW	without	(24)

The formulae in 5.3.2 are valid for nominal flux in the motor. If the CDM cannot provide the rated fundamental motor voltage to the motor at 100 % speed, the losses in the motor will be higher than in 5.3.2 calculated due to higher motor current. In order to consider this, the motor losses in Formula (27) shall be corrected.

Formula (26) gives the correction factor x,

$$x = \frac{U_{r,\,Mot}}{U_{fundamental,\,CDM}} \tag{26}$$

For the reference system the rated motor voltage is 400V and the fundamental voltage from the CDM is 360 V, which results in x=1,11.

In real existing systems the actual values of the rated motor voltage and the fundamental voltage of the CDM can be used.

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, Formula (27).

$$P_{L,PDS(n;T)} = P_{L,CDM(n;T)} + P_{LAux(n;T)} + P_{LMot(n;T)} \tag{27}$$

where

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

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

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

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 in Annex A .The losses calculation is done according to Formula (27) of the RCDM and RM. Exception to this is the 100 % speed and 100 % torque loss calculation of the RPDS, which is calculated in Formula (28) 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 for the RCDM is used in order to avoid overmodulation which would appear for 100 % frequency of the RCDM and would decrease the losses of the CDM but increase the harmonic losses of the motor due to higher harmonic content in the motor 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. The fundamental losses of the RM are assumed to increase compared to Formula (27) with the correction factor x = 1,11 according to Formula (26).

$$P_{L,RPDS(100;100)} = P_{L,RCDM(90;100)} + x \cdot P_{L,RM(100;100)} \tag{28}$$

Table 18 — Reference parameter for Formula (28)

Abbreviation	Description	Value	Unit
x	Correction factor of motor losses for the RPDS, see Formula (26)	1,11	

For the calculation of losses for an actual PDS, it is in the responsibility of the manufacturer to add all losses that are part of the PDS, e.g. Motor,CDM, Aux (filter , cable,…).

The following Table 19 shows the relative losses of the 400V/7,5kW reference PDS (RCDM and RM) at the operating points defined in Figure 5:

Table 19 — Relative losses of the 400V/7,5kW RPDS

$P_{\text{r,M}}$ / kW	$p_{\text{L,PDS, relative}}$ (0;25)	$p_{\text{L, PDS, relative}}$ (0;50)	$p_{\text{L, PDS, relative}}$ (0;100)	$p_{\text{L, PDS, relative}}$ (50;25)	$p_{\text{L, PDS, relative}}$ (50;50)	$p_{\text{L, PDS,relative}}$ (50;100)	$p_{\text{L, PDS,relative}}$ (100;50)	$p_{\text{L PDS, relative}}$ (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's with a different rated power are given in Table A.3.

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

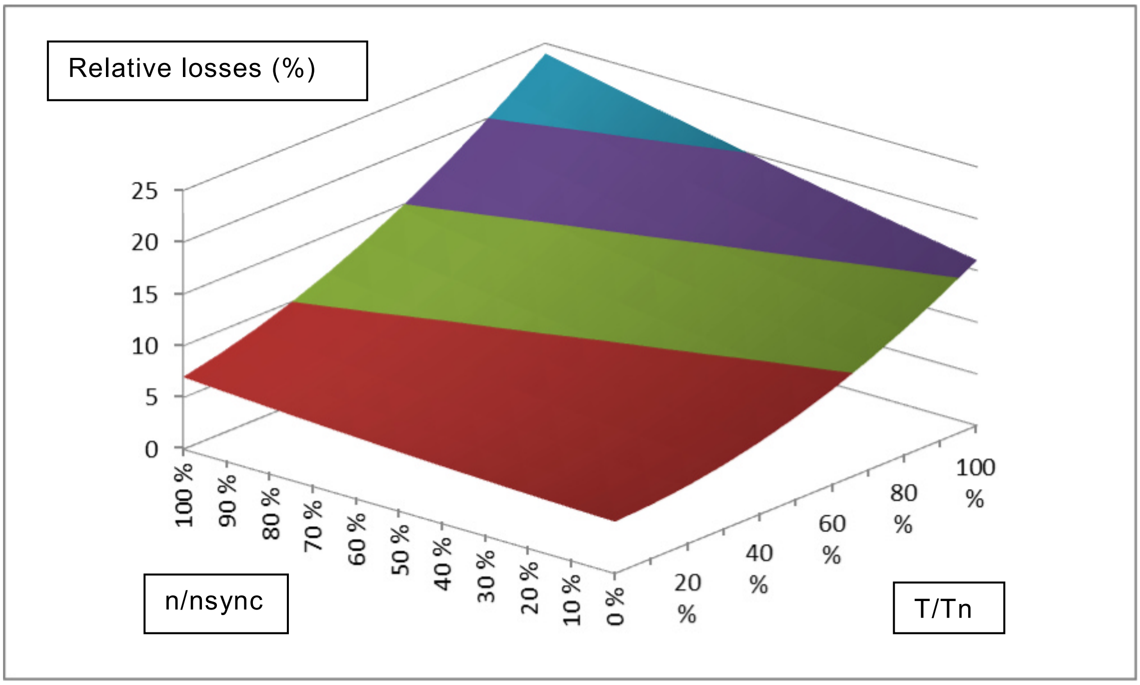


Figure 13 — Example of the relative power losses of PDS as function of speed and torque

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 the PDS for a dedicated switching frequency will be the sum of the electrical power losses of the subcomponents of the PDS , Formula (29), when the operating point (speed, torque) are kept constant.

$$P_{L,PDS(f_{sw})} = P_{L,CDM(f_{sw})} + P_{L,Aux(f_{sw})} + P_{L,Mot(f_{sw})} \tag{29}$$

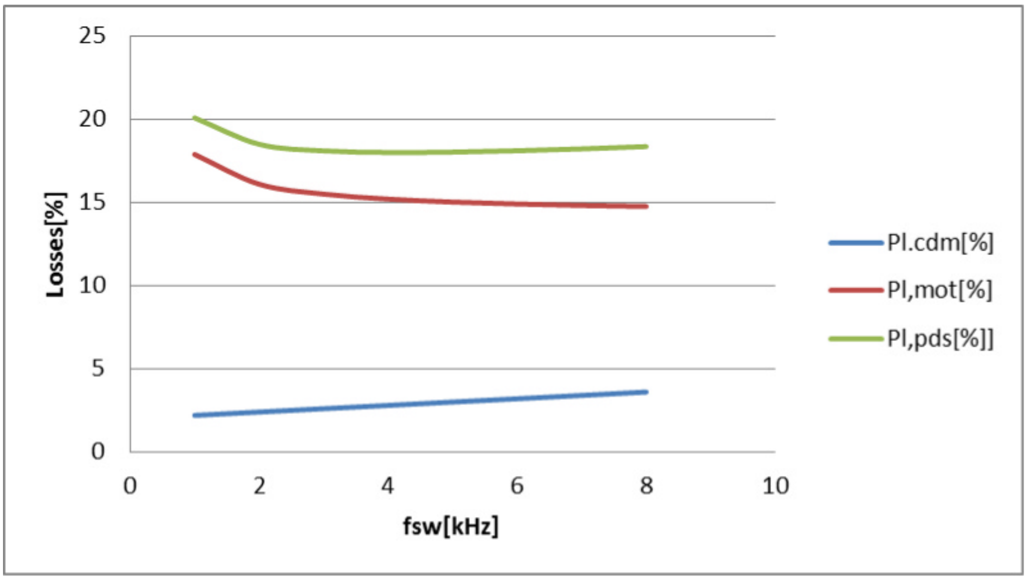


Figure 14 — Example of the relative power losses versus switching frequency

5.5 PDS losses for regenerative operation

PDS system can have the capability of handling generative loads that generate power. The generated power can be generated from decelerating the inertia of the load/motor or torque produced by the load e.g. draft in the fan. The CDM can have the capability to feed the extra generated power into the mains using an active infeed converter (AIC). The power fed to the mains is the generated power , less the losses of the PDS. The CDM can also have the capability to dissipate the extra power to heat inside or outside of the CDM, e.g. via a resistor. The power dissipated in the resistor is considered as auxiliary losses for PDS loss calculation, reference to Formula (27).The CDM can also have the capability to store the energy (battery or capacitors or similar technology) and this energy can be reused when motor power is needed. Energy storage for charging and discharging causes losses that have to be added as Aux losses when the losses of an extended product are calculated.

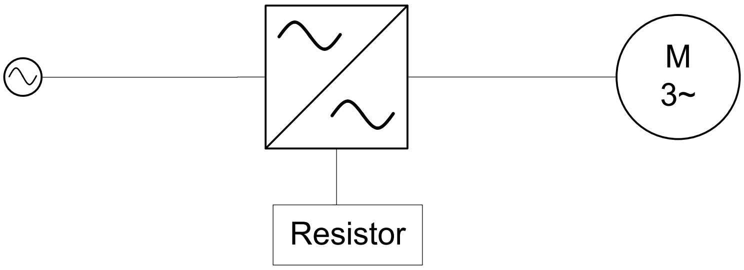


Figure 15 — Example of CDM with resistor for dissipating generated power

6 Power losses of motor starters

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

Soft starters according to the product standard EN 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.

7 Limits for IE and IES classes

7.1 General

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

Reference devices are associated with level 1. Existing devices with losses lower than the reference losses (i.e. better efficiency) are identified by levels higher than 1. The threshold and tolerance for each level are specified in the following clauses.

Compliance with an IE and IES class can be shown by either measurements or by calculations, which are described in Clause 9. The various test points shown in Figure 3 can be used to determine the losses and energy efficiency of an overall system for a specific application.

In order to reduce the certification process to a minimum, compliance with an IE and IES class shall be shown for the PDS at rated torque and rated speed and for the CDM at rated current and 90 % rated motor stator frequency, respectively rated motor voltage, only.

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

7.2 CDM

The reference CDM is described by the parameters given in 5.2. For power classes defined in IEC 60072-1 and IEC 60034-30, the losses of the reference CDM result in:

Table 20 — Reference CDM losses for IE class 1 definition

P_{rM} / kW	$S_{\mathrm{r,equ}}$ / kVA	$I_{\mathrm{r,out}}$ / A of the 400V RCDM	$p_{\mathrm{L,RCDM}\ (90,100)}$ / % of $S_{\mathrm{r,equ}}$	$P_{\mathrm{L,RCDM}\ (90,100)}$ / W
0,12	0,278	0,401	35,85	100
0,18	0,381	0,550	27,30	104
0,25	0,500	0,722	21,80	109
0,37	0,697	1,01	16,84	117
0,55	0,977	1,41	13,21	129
0,75	1,29	1,86	11,02	142
1,1	1,71	2,47	9,51	163
1,5	2,29	3,31	8,21	188
2,2	3,30	4,77	7,20	237
3	4,44	6,41	6,72	299
4	5,85	8,44	6,39	374
5,5	7,94	11,5	6,01	477
7,5	9,95	14,4	5,84	581
11	14,4	20,8	5,43	781
15	19,5	28,1	5,18	1010
18,5	23,9	34,4	5,05	1207
22	28,3	40,8	4,97	1408
30	38,2	55,2	4,87	1858
37	47,0	67,8	4,79	2253
45	56,9	82,1	4,75	2700
55	68,4	98,7	4,74	3239
75	92,8	134	4,69	4350
90	111	160	4,66	5169
110	135	195	4,11	5554
132	162	234	4,10	6645
160	196	283	4,09	8018
200	245	353	4,07	9976
250	302	436	4,10	12382
315	381	550	4,09	15594
355	429	619	4,09	17538
400	483	698	4,09	19764
500	604	872	4,08	24667
560	677	977	4,08	27628
630	761	1099	4,08	31064
710	858	1239	4,08	35006
800	967	1396	4,08	39434
900	1088	1570	4,08	44336
1 000	1209	1745	4,08	49267

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 $p_{\text{L,RCDM}}$ between those power ratings.

If the rated apparent output power of a CDM is between two values in Table 20, the relative loss value $p_{\text{L,RCDM}}$ of the RCDM with the next higher power rating shall be used for the IE class determination. The RCDM losses in Table 20 shall be used for all low voltage (100 V up and equal to 1 000 V) CDMs.

A CDM shall be classified as IE 1 if its relative losses are within ± 25 % of the value specified in Table 20.

A CDM shall be classified as IE 0 if its relative losses are more than 25 % higher than the value specified in Table 20.

A CDM shall be classified as IE 2 if its relative losses are more than 25 % lower than the value specified in Table 20.

Tolerances shall be taken into account according to Clause 9.

These definitions are illustrated in Figure 16:

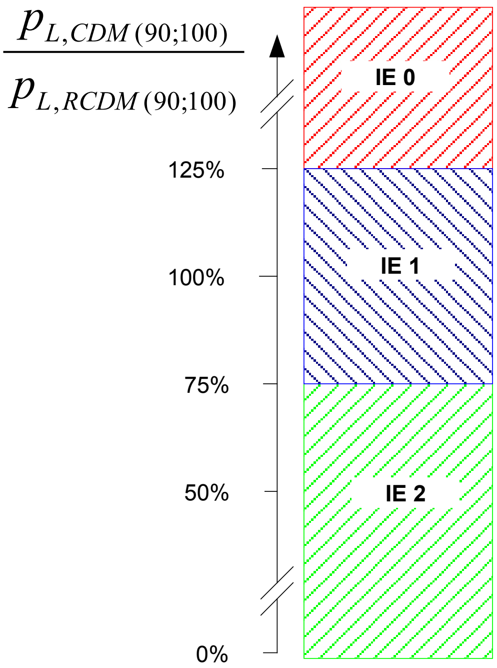


Figure 16 — Illustration of IE classes for a CDM

NOTE 2 In this edition of the standard, limit classes for CDM’s are defined up to IE 2 only. Classes IE 3 to IE 9 are reserved to describe future technological improvements of CDM’s.

In this edition of the standard, the determination of IE classes is only mandatory for CDM’s converting AC input power to AC output power.

7.3 Motor

In this edition of the standard, IE classes for motors operated on a CDM are not defined. They could be defined in a future standard IEC/TS 60034-30-2.

7.4 PDS

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

A PDS shall be classified as **IES 1** if its relative losses are within ± 20 % of the value specified in Table 21.

A PDS shall be classified as **IES 0** if its relative losses are more than 20 % higher than the value specified in Table 21.

A PDS shall be classified as **IES 2** if its relative losses are more than 20 % lower than the value specified in Table 21.

These definitions are illustrated in Figure 17:

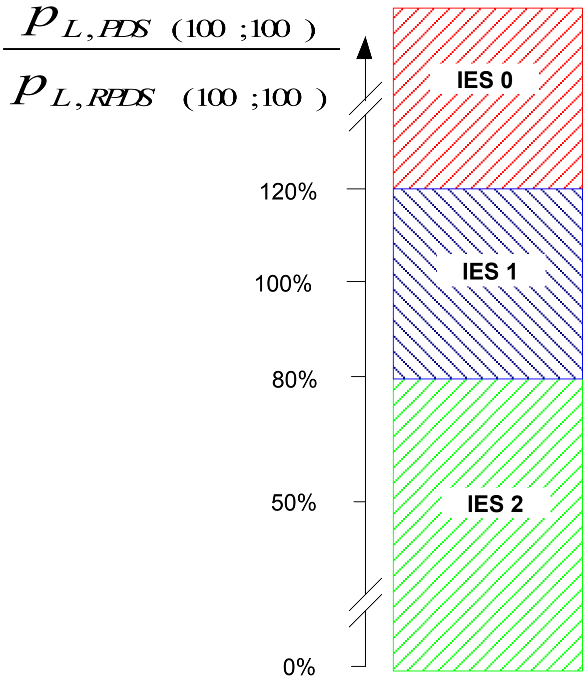


Figure 17 — Illustration of IES classes for a PDS

The reference PDS losses are described in 5.4.1. The losses of the reference PDS result in:

Table 21 — Reference PDS losses for IES class 1 definition

$P_{\mathrm{r,M}}$ / kW	$p_{\mathrm{L,RPDS}\ (100,100)}$ / % of $P_{\mathrm{r,M}}$	$P_{\mathrm{L,RPDS}\ (100,100)}$ / W
0,12	172,13	207
0,18	127,46	229
0,25	102,21	256
0,37	79,62	295
0,55	61,40	338
0,75	51,64	387
1,1	43,98	484
1,5	39,03	585
2,2	34,54	760
3	31,61	948
4	29,11	1164
5,5	26,57	1462
7,5	24,01	1801
11	21,60	2376
15	19,98	2997
18,5	18,84	3486
22	18,11	3983
30	16,84	5053
37	16,14	5973
45	15,46	6957
55	14,76	8120
75	13,95	10461
90	13,60	12243
110	13,12	14437
132	12,80	16895
160	12,47	19948
200	12,14	24274
250	12,10	30254
315	12,10	38114
355	12,09	42917
400	12,09	48360
500	12,08	60412
560	12,08	67662
630	12,08	76103
710	12,08	85764
800	12,08	96627
900	12,08	108677
1 000	12,08	120758

If the rated power of a PDS is between two values in Table 21, the next higher power RPDS loss value shall be used for the IES class determination.

8 Requirements for the user's documentation

8.1 General

The purpose of this Clause 8 is to define the information necessary to determine the energy losses of the CDM and the PDS. The information requirement is presented as Table 22, showing where the information shall be provided, followed by explanatory subclauses.

All energy efficiency relative equipment labels shall be given in the documentation.

The requirements of Clause 8 apply to all CDM and the PDS, unless otherwise stated.

The information provided shall ensure an energy efficiency classification of the CDM, PDS and it shall also provide sufficient information to ensure an energy efficiency classification for the final application and/or system where the CDM or PDS is used as a component.

The manufacturer shall define whether the rated test load stator frequency is 50 Hz or 60 Hz and give this information in the documentation:

Table 22 — Information requirements

Information	**Subclause**	**Location** [a, b]			**Technical subclause**
	reference	**1**	**2**	**3**	**reference**
For selection	8.2				
For determination of energy efficiency classes	8.3				
General	8.3			X	4.6, 4.7, 7.1, 7.2, 7.4, 9
Supply voltage amplitude phase to phase	8.3			X	4.6, 4.7, 7.1, 7.2, 7.4, 9
Supply voltage frequency (e.g. 50Hz, 60Hz)	8.3			X	4.6, 4.7, 7.1, 7.2, 7.4, 9
Rated test load stator frequency in case of CDM and rated motor speed (mechanical revolutions per minute) in case of PDS	8.3			X	4.6, 4.7, 7.1, 7.2, 7.4, 9
IE rating of CDM and IES rating of PDS	8.3			X	4.6, 4.7, 7.1, 7.2, 7.4, 9
For determination of additional energy losses and part load conditions	8.4			X	
General	8.4.1			X	Annex B, 4.2, 9
Losses in part load conditions	8.4.2			X	4.2, 9
Losses of auxiliaries and options	8.4.3			X	
Losses in stand-by mode	8.4.4			X	5.2.7
Losses in regenerative mode if regenerate mode is present	8.4.5			X	B.4.3, 5.5

[a] Location: 1. On product (see 8.1); 2. On packaging; 3. Product documentation.

[b] The product documentation requested by 8.4 may be supplied in electronic format. When more than one of any product is supplied to a single customer, it is not necessary to supply a manual with each unit, if acceptable to the customer.

8.2 Information for selection

Each part of a CDM or PDS that is supplied as a separate product shall be provided with information relating to its function and electrical characteristics as requested by the applicable product standards.

NOTE Typical examples of product standards are:

- EN 61800-2 for adjustable speed electric drive systems;
- EN 60947-4-1 for contactors and motor-starters - electromechanical contactors and motor-starters;
- EN 60947-4-2 for contactors and motor-starters - AC semiconductor motor controllers and starters.

8.3 Information for determination of energy efficiency classes

For the energy classification (IE/IES) of the CDM and PDS the manufacture shall provide information about the classification as determined in 4.6, 4.7, 7.2 and 7.4 and verified according to Clause 9.

A PDS IES rating shall be given in case where the motor and CDM are physically combined to a single unit or in case they are intended to be used in this combination only. In this case, an IE rating for the CDM is not required.

For a general purpose CDM, which is not intended to be sold and operated together with a specific motor, only the CDM IE rating is required. However, an IES rating for a combination of a CDM and a motor may be specified.

Information shall be added at the place where the IE/IES information is given that the boundary conditions of the IE/IES classification and loss determination are according to the specifications of the product. As a minimum, the following boundary conditions shall be stated:

- Supply voltage amplitude U_{mL1} phase to phase;
- Supply voltage frequency (e.g. 50 Hz, 60 Hz);
- Rated test load stator frequency in case of CDM and rated motor speed (mechanical revolutions per minute) in case of PDS.

8.4 Information on the determination of additional energy losses and part load conditions.

8.4.1 General

For the calculation of the energy efficiency classes in final applications or system (see 4.2, Figure 6), where the CDM and/or PDS are used as components as described in Annex B, the losses of the CDM or PDS are required. This also includes part load operation as well as applicable options needed for operation of this application.

8.4.2 Losses in part load conditions

The manufacturer shall state the losses of the CDM according to the part load measurement points as defined in 4.2 and verified according to Clause 9. In this edition of the standard, the information on losses is only mandatory only for CDM's converting AC input power to AC output power.

The manufacturer shall state the losses of the PDS according to the part load operation points as defined in 4.2 and verified according to Clause 9.

The number of part load operation points can be reduced, if the final application only requires a limited number of load points according to the extended product approach. If the manufacturer of the CDM/PDS only provides limited part load operation points to support specific applications, this shall be stated in the manual.

8.4.3 Losses of auxiliaries and options

If the losses of an individual optional EMI filter, line choke, transformer, external fan, output choke and output filter and other power consuming options, which is intended to be used together with the PDS or CDM for the operation in the final application, exceeds:

- 0,1 % of the rated CDM power and
- 5W totally

they shall be stated in the documentation at the operating point of rated power within a tolerance of ± 25 %, unless they are included in the CDM or PDS losses.

The same applies to motion controllers or application options which are specifically intended to be used together with the drive.

8.4.4 Losses in standby mode

The manufacturer shall state the power losses in stand-by mode of the CDM and PDS within a tolerance of + 25 %.

8.4.5 Losses in regenerative mode

It shall be stated in the user’s documentation whether a CDM or PDS is able to regenerate energy from the load to the mains or not.

The manufacturer shall provide sufficient information in order for the system integrator to calculate the losses of the CDM or PDS in regenerative mode based on the regenerative topology supported by the CDM or PDS.

9 Type testing

9.1 General

The purpose of this Clause 9 is to define type tests which shall be done for the CDM to verify IE class and for the PDS to verify IES class. Loss determination methods for IE energy classes of CDM and IES classes of PDS are considered as type testing of CDM and PDS in this standard. Furthermore, determination procedures for CDM and PDS losses in partial load conditions are defined.

If a CDM is specified with active power only, its output current shall be calculated according to Formula (4). Its rated apparent output power shall be calculated according to Formula (5).

Losses and IE/IES classes shall be calculated and measured at a rated input voltage according to IEC 60038:2009, Table 1. Furthermore, the rated equipment voltage and – in case of the PDS – rated motor speed shall be stated in the documentation.

9.2 Type testing of CDM for IE classification

The manufacturer shall make type tests to define IE energy efficiency classes for CDM. IE energy efficiency classes are defined based on single operation point according to 7.1 and losses in this point shall be determined using one of the following options:

- CDM losses are determined according to single component loss determination, described in 9.5.
- Power losses are determined based on input-output method for CDM according to 9.7. Testing procedure is given in 9.7.3.4 and testing conditions are described in 9.9.

- CDM losses are measured by means of calorimetric method according to 9.8. Testing conditions are described in 9.9.

The manufacturer can freely choose the loss determination method to determine losses.

NOTE The testing laboratories and other ones can use determination methods based on measurements: calorimetric or input-output determination method.

If a CDM is not able to operate an asynchronous motor, it shall be tested with an appropriate test load and the deviations from the test conditions described in 9.9 shall be stated in the user's documentation and the test report.

Required power losses for IE energy efficiency class calculation shall be calculated from determined losses $P_{L,CDM,determined}$ according to next formula

$$P_{L,CDM} = P_{L,CDM,determined} + \Delta P_{L,CDM} = P_{L,CDM,determined} \cdot \left(1 + \Delta p_{L,CDM} / 100\right) \tag{30}$$

This corrected power loss value shall be used to define relative power losses of CDM. The uncertainty of the used method shall be added to the determined loss value, as described in Figure 18 . The uncertainty of the determination method shall be determined by the manufacturer. The manufacturer is responsible to apply the correct uncertainty to power losses. The applied uncertainty shall be based on randomly occurring errors with normal distribution. Typical uncertainties for different determination methods and a calculation method for a loss uncertainty are given in Annex H.

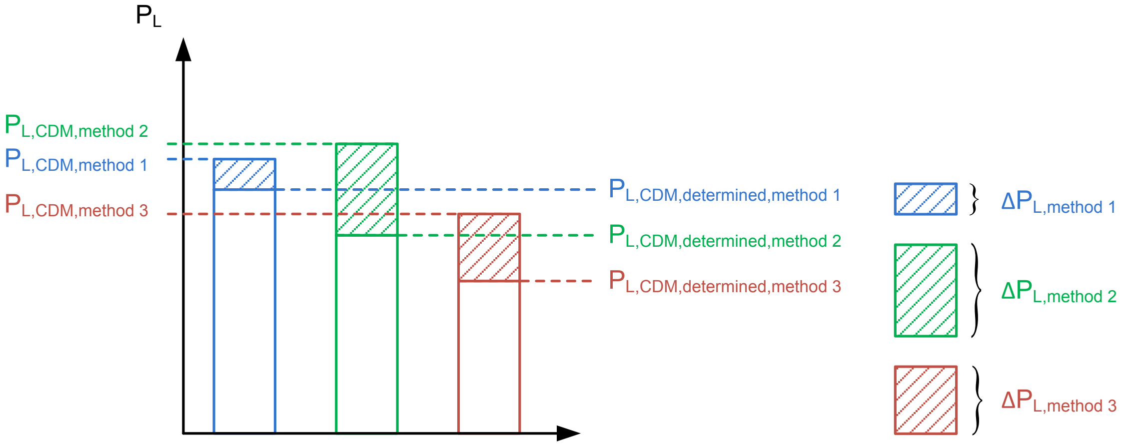


Figure 18 — Power loss of CDM is a sum of determined loss value and an uncertainty of the used determination method.

9.3 Type testing of PDS for IES classification

The manufacturer shall make type tests to define IES energy efficiency classes for PDS. IES energy efficiency classes are defined based on single operation point in 7.1 and losses in this point shall be determined by using one of the following options:

- PDS losses are determined according to 9.6.
- Power losses are determined based on input-output method according to 9.7. Testing procedure is given in 9.7.3.5 and testing conditions are described in 9.10.

The manufacturer can freely choose the loss determination method to determine losses.

NOTE The testing laboratories and other ones can use input-output determination method for loss determination.

Calorimetric measurement method for PDS is excluded since it is very difficult to perform for motors.

To define the IES energy efficiency class for a PDS, the manufacturer shall consider the uncertainty of the used loss determination method. Required power losses for IES energy efficiency class calculation shall be calculated from determined losses $P_{\mathrm{L,PDS,determined}}$ according to next formula:

$$P_{L,PDS} = P_{L,PDS,determined} + \Delta P_{L,PDS} = P_{L,PDS,determined} \cdot \left(1 + \Delta p_{L,PDS} / 100\right) \tag{31}$$

This corrected power loss value shall be used to define the relative power losses of a PDS. The uncertainty of the determination method shall be determined by the manufacturer. The manufacturer is responsible to apply the correct uncertainty to power losses. The uncertainty shall be based on randomly occurring errors with normal distribution. Typical uncertainties for different determination methods and a calculation method for a loss uncertainty are given in Annex H.

9.4 Determination procedures for CDM and PDS losses in part load operation

The manufacturer shall state the power losses of the CDM or PDS according to the part load points as defined in 4.2.

For the CDM, the losses shall be determined according to the same approach as for IE class determination in 9.2. The manufacturer shall state part load power losses for the CDM with uncertainties as described in Formula (30).

For the PDS, the losses shall be determined according to same approach as for IES class determination in 9.3. The manufacturer shall state part load power losses for PDS with uncertainties as described in Formula (31).

NOTE The testing laboratories and other ones can use determination methods based on measurements: calorimetric or input-output determination method.

9.5 Power loss calculations for CDM

For power loss determination of the CDM by calculation, the model presented in 5.2 can be used. The manufacturer is allowed to use an own calculation model to determine losses. Power loss simulations are allowed as well. Manufacturer is responsible to apply correct accuracies in Formula (30).

The CDM power loss calculations have to be performed, with respect to component manufacturer’s data with typical values of power semiconductors at actual temperature when operating the CDM or at maximum operating temperature specified in the datasheet. The power losses affecting parameters are determined for the components of the CDM in the operating points required. If for components no manufacturer’s data concerning power loss are available, they have to be evaluated by measurement. For some CDM components, losses are easily covered by measurements. Combination of measured and calculated losses is one possible way to determine losses for CDM. Finally, the different individual losses are calculated or measured separately and the total power losses of the CDM ($P_{\mathrm{L,CDM.determined}}$) are determined as the sum of all individual losses.

9.6 Power loss calculations for PDS

Power losses of the PDS can be determined by calculation according to Formula (27) and (28). When calculating PDS losses with a RCDM, no tolerances have to be added on CDM losses. If the PDS losses are calculated with the RM, tolerances according to EN 60034-1 shall be added to the final PDS.

9.7 Input-output measurement method

9.7.1 Input-output measurement of CDM losses

Input-output determination method for CDM losses is based on electrically measured powers at input and output of the CDM. Measurement setup is illustrated in Figure 19. The measured power losses of the CDM shall be calculated by using the following formula:

$$P_{L,CDM,determined} = P_{in,CDM} - P_{out,CDM} \tag{32}$$

Input power P_{in} is determined based on measured input voltages U_{in} and input currents I_{in} by a power analyzer. Respectively, output power P_{out} is determined based on output voltages U_{out} and currents I_{out} measured by a power analyzer. The measurement of the CDM output shall be done directly at the output terminals of the CDM. In this method the accuracy is limited by the accuracy available measurement equipment.

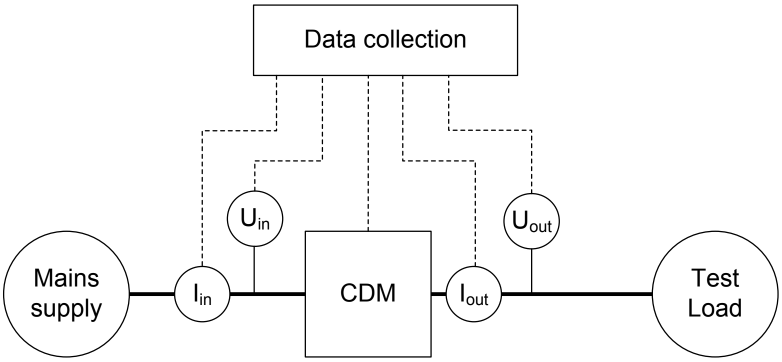


Figure 19 — Input-output measurement setup for CDM losses.

9.7.2 Input-output measurement of PDS losses

Input-output determination method for PDS losses is based on electrically measured electric power in input and mechanical power of PDS in output. Measurement setup is illustrated in Figure 20. Determined power loss of the PDS shall be calculated by using the formula

$$P_{L,PDS,determined} = P_{in,PDS} - P_{out,PDS} \tag{33}$$

Input power $P_{in,PDS}$ is determined based on input voltages U_{in} and input currents I_{in} measured by a power analyzer. Respectively, output power $P_{out,PDS}$ is determined based on measured torque and speed of the motor. In this method the accuracy is limited by the accuracy of the measurement equipment.

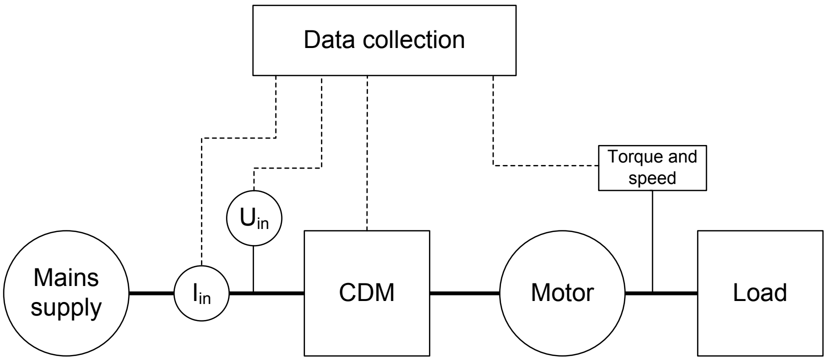


Figure 20 — Input-output measurement setup for PDS losses.

9.7.3 Requirements for input-output measurement method

9.7.3.1 General

When testing CDM or PDS under load, slow fluctuations in the output power and other measured quantities may be unavoidable. Therefore for each load point several measurements over a period of time (at least several slip cycles, typically 1 min to 3 min) shall be simultaneously sampled and the average of these values shall be used for the determination of losses.

Considering the harmonics involved in converters, the measuring equipment has to be selected according to the range of relevant frequencies with sufficient accuracy.

9.7.3.2 Power analyzer and transducers

The instrumentation for measuring power and current at the CDM's input or output shall meet the requirements of EN 60034-2-1.

The uncertainty specified by the instrument manufacturer of the power meters shall be 0,2 % of S_{equ} or better for the total active power at 50/60 Hz. This is the total uncertainty for the power meter including possible sensors.

The bandwidth of power meter and sensors shall be such wide, that the error of the total active power due to the limited bandwidth does not exceed 0,3 % of S_{equ}.

NOTE 1 The apparent output power of a CDM at switching frequency is typically not more than 5 % of the total rated output power and reduces according to a square function with higher frequencies. Therefore, a bandwidth from 0 Hz up to 10 times of f_{sw} for PWM converter output is sufficient.

The measurement range shall be chosen adequately in relation to the measured currents and voltages.

It is preferred to feed current and voltage directly into the power analyzer. If an external current transducer is required, inductive transducer, wide bandwidth shunts or zero-flux transducers can be used.

NOTE 2 If DC components are present, inductive transducers are not applicable.

NOTE 3 Inductive transducers have bigger uncertainties and/or amplitude limitations for smaller frequencies than nominal frequency.

All cables used to transmit measurement signals shall be carefully installed and should be shielded, if possible.

9.7.3.3 Mechanical output of the motor

The instrumentation for measuring torque and speed at the motor's output shall meet the requirements of EN 60034-2-1.

9.7.3.4 Measurement procedure for input-output method of CDM loss determination

The following measurement procedure produces data for 8 required loss values of a CDM. Procedure starts with an initial need to heat up the CDM, and to achieve stable temperature at rated speed and load. The test procedure includes three further periods of operation at lower speeds and torques. The order in which the tests and measurements are carried out is shown in Figure 21 by means of the bracketed numbers. At all test points, the relative CDM output voltage shall be no lower than the relative CDM output frequency.

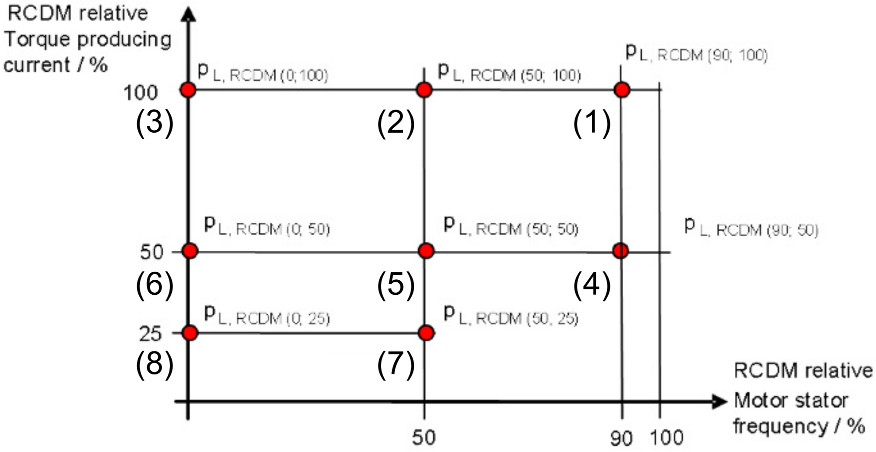


Figure 21 — Order in which measurements shall be made for CDM: (1) to (8).

The CDM is firstly run at 90 % of frequency and 100 % of current (1) until the CDM has achieved thermal stability. Stability has been achieved when the rate of temperature rise is less than 2 K per hour.

When thermal stability has been achieved, measure and record voltage, current, power and power factor both at the input and output of the CDM. All other loading points shall be measured immediately after Point (1).

With the current setting unchanged, measure and record the above quantities with frequencies of 50 % (2) and 0 % (3) of rated value.

Reduce the CDM torque producing current to 50 % of its rated value, and measure and record the above quantities with frequencies of 90 % (4), 50 % (5) and 0 % (6) of rated value.

Reduce the CDM torque producing current to 25 % of its rated value, and measure and record the above quantities with frequencies of 50 % (7) and 0 % (8) of rated value.

In order to overcome limitations of the available commercial measuring equipment in low frequencies it is also acceptable to give the CDM losses for a frequency of up to 5 Hz instead of zero frequency.

9.7.3.5 Measurement procedure for input-output method of PDS loss determination

The following measurement procedure produces data for 8 required loss values of a PDS. Procedure starts with an initial need to heat up the PDS, and to achieve stable temperature at rated speed and load. The test procedure includes three further periods of operation at lower speeds and torques. The order in which the tests and measurements are carried out is shown in Figure 22 by means of the bracketed numbers.

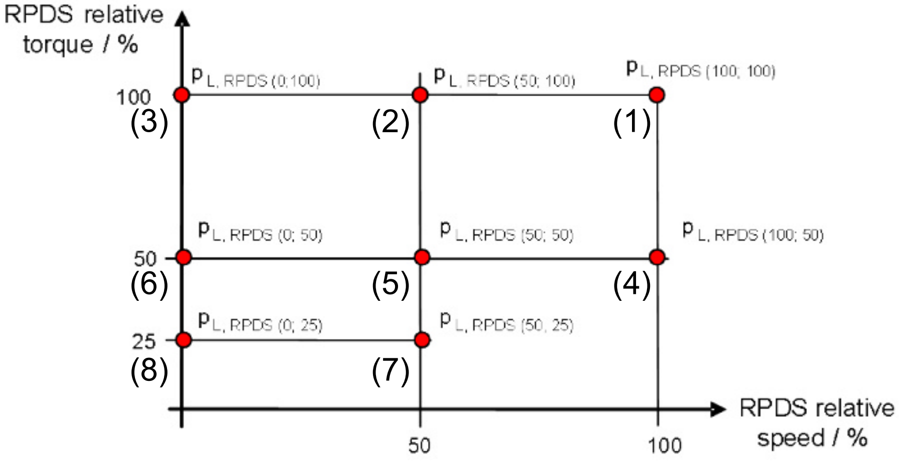


Figure 22 — Order in which measurements shall be made for PDS: (1) to (8).

The PDS is firstly run at full rated speed and torque (1) until the motor temperature-rise (defined as the external motor temperature minus ambient air temperature) is stable. Stability has been achieved when the rate of temperature rise is less than 2 K per hour, at which time the power electronic equipment associated with the motor is also be deemed to have achieved thermal stability.

When thermal stability has been achieved, measure and record supply voltage, current, power and power factor, and shaft torque and speed. All other loading points shall be measured immediately after point (1).

With the torque setting unchanged, measure and record the above quantities with speed of 50 % (2) and 0 % (3) of rated value.

Reduce the motor torque to 50 % of its rated value, and measure and record the above quantities with speed of 100 % (4), 50 % (5) and 0 % (6) of rated value.

Reduce the motor torque to 25 % of its rated value, and measure and record the above quantities with speed of 50 % (7) and 0 % (8) of rated value.

In order to overcome limitations of the available commercial measuring equipment in low frequencies the PDS losses can also be given for a speed corresponding to up to 5Hz stator frequency instead of zero speed.

9.8 Calorimetric measurement of CDM losses

In calorimetric measurements for CDM losses, the power losses are measured by means of cooling medium flow and temperatures. Measurement setup for determining CDM losses is presented in Figure 23. Required data is collected also from CDM operation state for documentation. Testing conditions are described in 9.9. Detailed test methods and procedures are described in Annex I.

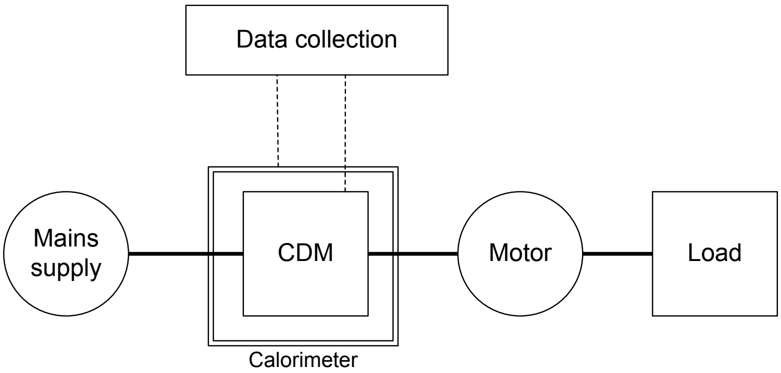


Figure 23 — Calorimetric measurement setup for determining CDM losses.

9.9 Testing conditions for CDM testing

For the application of measurement methods, the test conditions and test procedure are of high importance for the results and for the reproducibility and comparability of different manufacturers and test laboratories. Due to this certain boundary conditions should be kept and documented or some others only be documented.

- Switching frequency and pulse pattern of CDM shall be factory setting as defined by the manufacturer and are to be documented.
- The operating points shall be defined according to Figure 21.
- At all test points, the relative CDM output voltage shall be no lower than the relative CDM output frequency.
- The measurement shall be done according to the measurement procedure described in 9.7.3.4.
- CDM input voltage and frequency have to be rated values of the CDM.
- The crest factor of the supply voltage shall be between 1,35 and 1,44.
- Short circuit ratio of CDM and supply network shall be in range from 50 to 200 up to 90 kW and from 5 to 50 above 90 kW.
- The CDM shall be loaded by means of the defined test load and loaded (electrically or mechanically) under the conditions with respect to required torque and speed. CDM output current shall be according to Table 2. Higher inverter output current leads to increased losses, so test shall be performed with a current no lower than specified in Table 2. It is possible to use an electronic load instead of a motor. The displacement factor of the load fundamental current referred to the fundamental voltage shall be according to Table 3 with a tolerance of ± 0,08. In case the rated CDM output current is between two values of Table 20, the next larger motor is expected to fulfil the tolerance requirement.
- The test load for the CDM loss measurement has to be chosen in a way that the THD of the CDM fundamental output current is lower or equal to 5 %. Higher distortion will lead to increased CDM losses.
- Unless otherwise specified, CDMs having rated power below 20 kW shall be measured with a minimum 15 m shielded cable. If a rating of motor cable for CDM is less than 15 m, the maximum cable length shall be used.

- The CDM shall be equipped and installed to fulfil the requirement of EN 61800-5-1 with respect to electrical safety.
- The power losses have to be determined in continuous operation.
- The tests can be done at any temperature.
- Measurements shall be made with cooling system at full performance. In case cooling is temperature dependent with the cooling system going e.g. on/off or PWM, an average measurement over 10 min is allowed for each measuring point for the testing clauses.

9.10 Testing conditions for PDS testing

- The operating point shall be defined according to Figure 22.
- The measurement shall be done according to measurement procedure described in 9.7.3.5.
- CDM input voltage and frequency have to be rated values of the CDM.
- The crest factor of the supply voltage shall be between 1,35 and 1,44.
- Short circuit ratio of CDM and supply network shall be in range from 50 to 200 up to 90 kW and from 5 to 50 above 90 kW.
- Unless otherwise specified, PDSs having rated power below 20 kW shall be measured with a minimum 15 m shielded cable. If rating of motor cable for PDS is less than 15 m, the maximum cable length shall be used. For integrated PDS, there is no requirement for cable lengths.
- The tests can be done at any temperature. A temperature correction shall be applied for motor losses according to EN 60034-2-1.
- Measurements shall be made with cooling system at full performance. In case cooling is temperature dependent with the cooling system going e.g. on/off or PWM, an average measurement over 10 min is allowed for each measuring point for the testing clauses.

Annex A

(informative)

Losses of the RCDM, RM and RPDS

Table A.1 — Relative losses (%) of the reference CDM’s, based on 400V RCDM of different power ratings at the operating points described in Figure 5

P_rM / kW	$S_{r,equ}$ /kVA	$p_{L,RCDM,}$ relative (0;25)	$p_{L,RCDM,}$ relative (0;50)	$p_{L,RCDM,}$ relative (0;100)	$p_{L,RCDM,}$ relative (50;25)	$p_{L,RCDM,}$ relative (50;50)	$p_{L,RCDM,}$ relative (50;100)	$p_{L,RCDM,}$ relative (90;50)	$p_{L,RCDM,}$ relative (90;100)
0,12	0,278	33,79	33,84	34,30	33,89	34,04	34,84	34,39	35,85
0,18	0,381	25,24	25,28	25,75	25,34	25,48	26,28	25,83	27,30
0,25	0,5	19,74	19,78	20,25	19,84	19,99	20,78	20,34	21,80
0,37	0,697	14,77	14,82	15,29	14,87	15,02	15,82	15,37	16,84
0,55	0,977	11,14	11,19	11,66	11,24	11,39	12,19	11,74	13,21
0,75	1,29	8,96	9,00	9,47	9,06	9,20	10,00	9,55	11,02
1,1	1,71	6,86	7,13	7,82	6,93	7,33	8,40	7,68	9,51
1,5	2,29	5,56	5,83	6,52	5,63	6,03	7,10	6,38	8,21
2,2	3,3	4,54	4,82	5,51	4,61	5,02	6,09	5,37	7,20
3	4,44	4,07	4,35	5,04	4,14	4,55	5,62	4,90	6,72
4	5,85	3,74	4,02	4,71	3,82	4,22	5,29	4,57	6,39
5,5	7,94	3,35	3,63	4,32	3,42	3,83	4,90	4,18	6,01
7,5	9,95	2,80	3,09	4,02	2,86	3,28	4,64	3,61	5,84
11	14,4	2,39	2,68	3,61	2,46	2,87	4,23	3,20	5,43
15	19,5	2,15	2,44	3,37	2,22	2,63	3,99	2,96	5,18
18,5	23,9	2,02	2,32	3,24	2,09	2,51	3,86	2,83	5,05
22	28,3	1,94	2,23	3,16	2,01	2,43	3,78	2,75	4,97
30	38,2	1,83	2,12	3,05	1,90	2,31	3,67	2,64	4,87
37	47	1,76	2,05	2,98	1,83	2,24	3,60	2,57	4,79
45	56,9	1,71	2,01	2,93	1,78	2,20	3,55	2,52	4,75
55	68,4	1,62	1,93	2,90	1,70	2,13	3,53	2,47	4,74
75	92,8	1,58	1,88	2,85	1,65	2,08	3,48	2,42	4,69
90	111	1,55	1,86	2,82	1,62	2,05	3,45	2,39	4,66
110	135	1,24	1,48	2,27	1,32	1,68	2,91	2,02	4,11
132	162	1,23	1,47	2,26	1,30	1,67	2,89	2,01	4,10
160	196	1,22	1,46	2,25	1,29	1,66	2,88	2,00	4,09
200	245	1,21	1,45	2,24	1,28	1,65	2,87	1,98	4,07
250	302	1,17	1,42	2,24	1,24	1,61	2,88	1,95	4,10
315	381	1,16	1,41	2,23	1,23	1,61	2,87	1,94	4,09
355	429	1,16	1,41	2,23	1,23	1,60	2,87	1,94	4,09
400	483	1,16	1,41	2,23	1,23	1,60	2,87	1,94	4,09
500	604	1,15	1,40	2,22	1,22	1,60	2,86	1,94	4,08
560	677	1,15	1,40	2,22	1,22	1,60	2,86	1,93	4,08
630	761	1,15	1,40	2,22	1,22	1,60	2,86	1,93	4,08
710	858	1,15	1,40	2,22	1,22	1,59	2,86	1,93	4,08
800	967	1,15	1,40	2,22	1,22	1,59	2,86	1,93	4,08
900	1088	1,15	1,39	2,21	1,21	1,59	2,85	1,93	4,08
1 000	1209	1,14	1,39	2,21	1,21	1,59	2,85	1,93	4,08

Table A.2 — Relative losses (%) of 50Hz-4-pole reference motors (IE2) for different power ratings at the operating points described in Figure 4

P_{N} / kW	$p_{\mathrm{L,RM,}}$ (0;25)	$p_{\mathrm{L, RM,}}$ (0;50)	$p_{\mathrm{L,RM,}}$ (0;100)	$p_{\mathrm{L,RM,}}$ (50;25)	$p_{\mathrm{L,RM,}}$ (50;50)	$p_{\mathrm{L,RM,}}$ (50;100)	$p_{\mathrm{L,RM,}}$ 100;50)	$p_{\mathrm{L,RM,}}$ (100;100)
0,12	28,9	32,8	59,9	36,6	40,5	66,8	51,5	79,6
0,18	23,8	27,1	47,3	30,6	33,8	53,4	44,4	62,7
0,25	19,5	22,4	38,0	25,3	28,1	43,2	37,5	52,9
0,37	15,0	17,6	30,7	19,5	22,1	34,4	28,9	43,2
0,55	11,7	14,4	27,7	15,0	17,7	30,1	21,8	34,2
0,75	9,3	11,7	22,8	12,1	14,5	24,7	19,2	29,5
1,1	7,4	9,7	20,5	10,0	12,3	22,2	16,2	26,3
1,5	6,0	8,2	17,9	8,3	10,8	19,7	14,0	23,9
2,2	5,2	7,2	15,5	7,4	9,4	17,9	12,7	21,4
3	4,5	6,3	13,8	6,5	8,3	16,2	11,4	19,5
4	3,8	5,4	12,2	5,6	7,3	14,4	10,2	17,8
5,5	3,0	4,4	10,5	4,7	6,1	12,6	8,8	16,1
7,5	2,5	3,7	9,3	4,0	5,3	11,2	7,8	14,7
11	2,2	3,4	8,7	3,6	4,9	10,4	7,2	13,1
15	1,8	3,0	7,5	3,1	4,3	9,2	6,4	11,9
18,5	1,7	2,8	7,1	2,9	4,0	8,7	5,9	11,1
22	1,6	2,6	6,8	2,8	3,8	8,3	5,7	10,5
30	1,5	2,3	6,2	2,5	3,4	7,5	5,2	9,6
37	1,3	2,1	5,6	2,4	3,2	6,9	4,9	9,1
45	1,2	1,9	5,0	2,2	2,9	6,3	4,7	8,5
55	1,1	1,7	4,3	2,1	2,7	5,6	4,6	8,0
75	1,0	1,3	3,5	2,0	2,4	4,8	4,4	7,3
90	1,0	1,3	3,5	1,9	2,2	4,6	4,1	7,1
110	1,0	1,4	3,2	2,2	2,7	4,7	4,7	7,3
132	1,0	1,4	3,2	1,9	2,5	4,6	3,9	7,0
160	1,0	1,4	3,1	1,8	2,4	4,6	3,9	6,7
200	1,0	1,4	3,1	1,8	2,3	4,5	3,8	6,4
250	1,0	1,4	3,0	1,8	2,3	4,4	3,8	6,4
315	0,9	1,3	3,0	1,8	2,3	4,3	3,8	6,4
355	0,9	1,3	2,9	1,8	2,3	4,3	3,8	6,4
400	0,9	1,3	2,9	1,8	2,3	4,2	3,8	6,4
500	0,9	1,3	2,8	1,8	2,3	4,2	3,8	6,4
560	0,9	1,3	2,7	1,8	2,3	4,1	3,8	6,4
630	0,9	1,3	2,6	1,8	2,3	4,1	3,8	6,4
710	0,9	1,3	2,6	1,8	2,3	4,1	3,8	6,4
800	0,9	1,3	2,5	1,8	2,3	4,0	3,8	6,4
900	0,9	1,3	2,4	1,8	2,3	3,9	3,8	6,4
1 000	0,9	1,3	2,4	1,8	2,3	3,8	3,8	6,4

NOTE 1 The factor for the additional losses in the motor due to converter fed operation changes according to 5.2.2.6. from 15 % to 25 % between the output powers of 90 kW and 110 kW. This causes a discontinuity in the tablular values

The basis for Table A.2 is the same as for Table 17 in 5.3.3, the last column in Table A.2 matches with the second column in Table 17.

NOTE 2 The loss calculation of RPDS at 100 % speed is the sum of RCDM and RM according to Formula (28).

Table A.3 — Relative losses (%) for a reference PDS, based on a 400V RCDM and 4-pole reference motors (IE2) at different power ratings and at the operating points described in Figure 3

P_{r},M / kW	$p_{\mathrm{L,PDS}}$, relative (0;25)	$p_{\mathrm{L,\ PDS}}$, relative (0;50)	$p_{\mathrm{L,RPDS}}$, relative (0;100)	$p_{\mathrm{L,PDS}}$, relative (50;25)	$p_{\mathrm{L,PDS}}$, relative (50;50)	$p_{\mathrm{L,PDS}}$, relative (50;100)	$p_{\mathrm{L,PDS}}$, relative (100;50)	$p_{\mathrm{L,PDS}}$, relative (100;100)
0,12	107,2	111,2	139,4	115,1	119,4	147,5	136,8	172,1
0,18	77,22	80,61	101,80	84,24	87,73	109,0	104,0	127,5
0,25	58,98	61,96	78,50	64,98	68,08	84,76	82,31	102,2
0,37	42,82	45,52	59,50	47,51	50,39	64,20	61,03	79,62
0,55	31,49	34,28	48,41	34,97	37,93	51,75	45,05	61,40
0,75	24,71	27,18	39,09	27,68	30,32	41,90	37,74	51,64
1,1	18,06	20,78	32,66	20,77	23,69	35,26	29,92	43,98
1,5	14,49	17,10	27,85	16,90	20,01	30,54	25,28	39,03
2,2	12,01	14,43	23,77	14,32	16,93	27,04	22,15	34,54
3	10,52	12,74	21,26	12,63	15,03	24,52	19,91	31,61
4	9,27	11,28	19,09	11,19	13,47	22,14	18,01	29,11
5,5	7,84	9,64	16,74	9,64	11,63	19,67	15,80	26,57
7,5	6,21	7,80	14,63	7,79	9,65	17,36	13,45	24,01
11	5,33	6,91	13,43	6,82	8,66	15,94	12,18	21,60
15	4,60	6,17	11,88	5,99	7,72	14,39	10,95	19,98
18,5	4,31	5,80	11,29	5,60	7,24	13,69	10,21	18,84
22	4,10	5,47	10,86	5,39	6,93	13,16	9,86	18,11
30	3,83	5,00	10,08	4,92	6,34	12,17	9,13	16,84
37	3,54	4,70	9,39	4,72	6,05	11,47	8,70	16,14
45	3,36	4,44	8,70	4,45	5,68	10,79	8,40	15,46
55	3,11	4,10	7,91	4,21	5,35	9,99	8,18	14,76
75	2,95	3,63	7,03	4,04	4,97	9,11	7,88	13,95
90	2,91	3,59	6,98	3,90	4,73	8,86	7,50	13,60
110	2,52	3,22	5,99	3,82	4,76	8,27	7,70	13,12
132	2,51	3,20	5,97	3,50	4,55	8,15	6,80	12,80
160	2,49	3,19	5,86	3,38	4,43	8,13	6,78	12,47
200	2,48	3,18	5,84	3,37	4,32	8,02	6,64	12,14
250	2,41	3,12	5,71	3,30	4,24	7,88	6,57	12,10
315	2,30	3,01	5,70	3,29	4,25	7,77	6,56	12,10
355	2,30	3,00	5,59	3,29	4,23	7,77	6,56	12,09
400	2,30	3,00	5,59	3,29	4,23	7,67	6,56	12,09
500	2,29	2,99	5,48	3,27	4,23	7,65	6,56	12,08
560	2,29	2,99	5,38	3,27	4,23	7,56	6,55	12,08
630	2,29	2,99	5,28	3,27	4,23	7,55	6,55	12,08
710	2,29	2,99	5,28	3,27	4,22	7,56	6,55	12,08
800	2,29	2,99	5,18	3,27	4,22	7,46	6,55	12,08
900	2,29	2,98	5,07	3,26	4,22	7,35	6,55	12,08
1 000	2,28	2,98	5,07	3,26	4,22	7,25	6,55	12,08

Annex B
(informative)

Description of the elements of an extended product using PDS with regard to their impact on losses

B.1 General

A PDS is used to supply power from the mains to the motor in applications that require varying the speed of a motor. The PDS can control the speed and/or the torque as required by the application and its control.

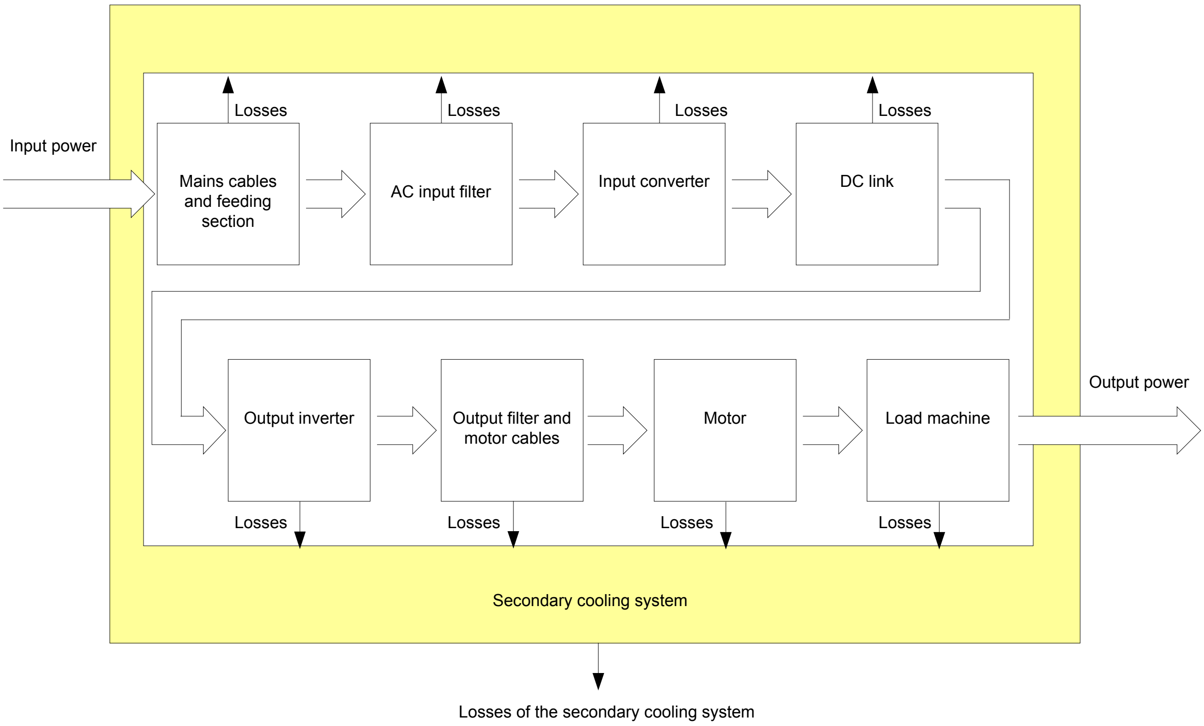


Figure B.1 — Overview of the extended product and energy flow

In Figure B.1, the complete system transferring energy from the mains to the load is illustrated. Mains cabling and the load machine are not a part of the PDS, though their losses might be important to evaluate an energy efficient extended product, see Annex A. In order to determine the overall energy efficiency, the complete system has to be evaluated. In particular, optimizing the energy efficiency of single subsystems is not a favourable solution, as these local optimizations might reduce the overall energy efficiency. In this chapter, the major dependencies are described.

B.2 Losses in the mains cabling and feeding section

The basic equivalent circuit for a three phase mains supply at the point of common coupling is shown in Figure B.2:

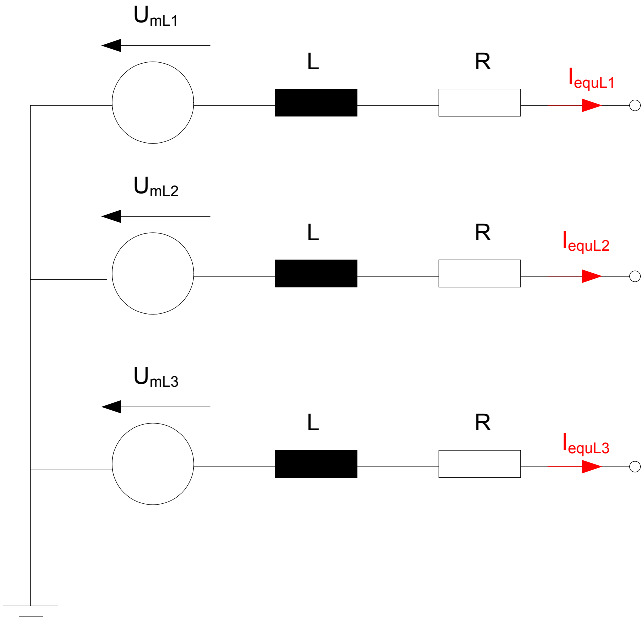


Figure B.2 — Equivalent circuit of the mains and mains cabling

In Figure B.2, a three phase power supply system with star point grounding is illustrated. As far as energy losses are concerned, the behaviour of other types of mains configurations such as delta grounding or single phase supply is identical. In a first approximation, the mains can be regarded as an ideal 50 Hz or 60 Hz power source. This power source has a series impedance, which is dominated by an inductive and an ohmic component. The ohmic component consists of the resistive part of mains cables, switches and fuses.

Energy losses are created in the ohmic part of the equivalent circuit. These losses increase with the square of the amount of current flowing in the mains. Assuming that all currents are identical in amplitude and shifted by 120°, the mains losses are:

$$P_{L,mains} = 3 \cdot R \cdot I_{L1}{}^{2} \tag{B.1}$$

Assuming a PDS connected to the mains in Figure B.2, the mains losses depend on the input current of the PDS. As a minimum, the PDS has to consume the active power required by the load and the losses generated by the PDS itself. However, the PDS might require additional apparent power due to reactive power and harmonic currents. The ratio between active power and apparent power (power factor) is defined:

$$\lambda = \frac{P_{equ}}{S_{equ}} = \frac{3 \cdot U_{mL1} \cdot I_{1,equ} \cdot \cos\varphi_{equ}}{3 \cdot U_{mL1} \cdot I_{equ}} = \frac{I_{1,equ} \cdot \cos\varphi_{equ}}{I_{equ}} \tag{B.2}$$

A PDS with λ close to 1 will lead to minimum losses in the mains. The value of λ is determined mainly by the input filter and the input converter of the PDS.

B.3 Input filter

B.3.1 High frequency EMI filter

High frequency EMI filters are used to limit high frequency emissions of the PDS according to EN 61800-3 in order not to disturb radio services. Maximum permitted emissions of a PDS depend on the environment in which the PDS is used.

In general the design of high frequency EMI-filters is influenced by applicable compliance parameters. Consideration is typically given to compliance with:

- low leakage current according to EN 61800-5-1, (e.g. Compliance with residual current devices or compliance with the 3,5/10 mA limit with respect to the requirement for the dimension of the protective earth connection.)
- support of shielded motor cable length,
- requirement in different environment according to EN 61800-3.

This will require different designs of the EMI filter including the EMI coil and therefore have a significant influence on the losses in the EMI coil.

The losses in RFI-filter may have a perceivable impact on the losses of a PDS, especially at low rated power.

B.3.2 Low frequency line harmonics filter

Low frequency line harmonics filters are used in some cases to reduce the voltage distortion of the mains voltage and therefore to ensure compatibility to other loads connected to the mains.

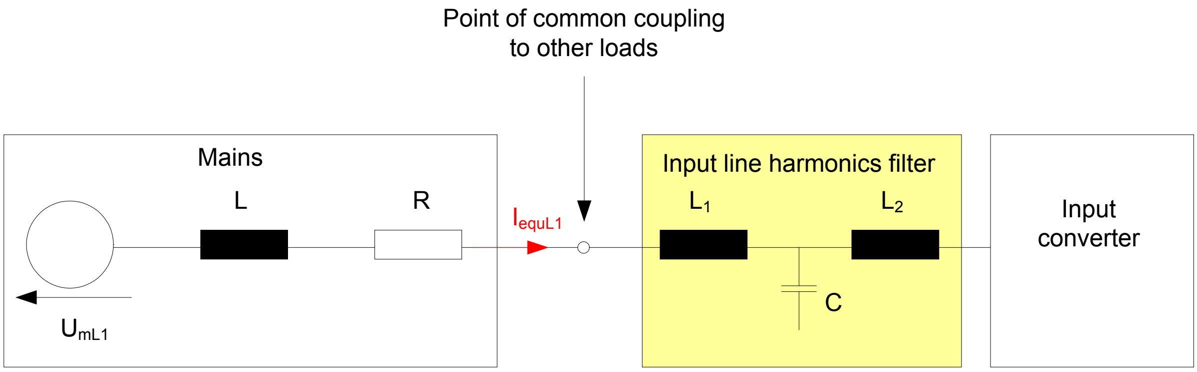


Figure B.3 — Illustration of a single phase line harmonics filter

An input line harmonic filter usually contains at least one series choke L_2. More sophisticated filter topologies contain additional components such as a parallel capacitor or an additional line side choke L_1.

As described in B.2, reducing harmonics leads to lower losses in the mains. On the other hand, inductive components in the filter increase the reactive power of the PDS, increasing mains losses. Additional losses are created in the filter components themselves. These positive and negative effects increase with larger filters.

B.4 Input converter

B.4.1 General

The input converter transfers energy from the three phase AC mains to the DC link. For the input converter, mainly two topologies can be found in PDS today:

B.4.2 Diode rectifier

Diode rectifiers are the most cost effective solution for input converters. At positive energy flow from the mains to the load, this topology has low losses, as the forward voltage drop of the diodes is relatively low and their switching frequency is the fundamental frequency of the power supply system only.

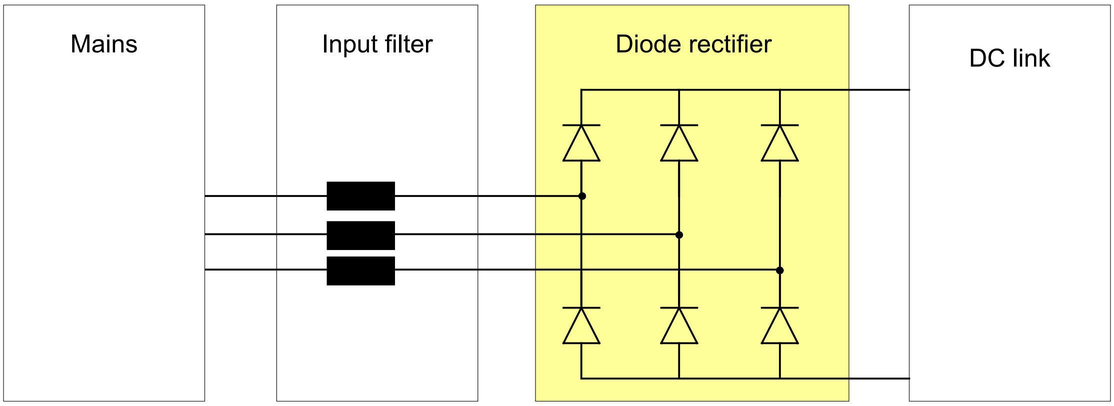


Figure B.4 — PDS with a diode rectifier input converter

On the other hand, diode rectifiers create relatively large harmonics in the mains current. These harmonic currents create losses in the mains. As described in B.3.2, these harmonic currents can be reduced by line chokes, DC link coils or line harmonic filters, which themselves create losses.

At negative energy flow, diode rectifiers are not able to regenerate energy from the load to the mains. The energy generated in the load, e.g. during braking, has to be dissipated in resistors. For applications with a significant regeneration, this reduces the overall energy efficiency performance of the system significantly, see 5.5. If the DC link of several CDMs are connected, the regenerative energy can be distributed via a common DC-link to supply other CDMs/PDSs.

As a special variant of diode rectifiers, some or all diodes can be replaced by thyristors. As these thyristors are mainly used for the precharge of the DC link capacitor, the behaviour of this type of converter is nearly identical to the diode rectifier during normal operating conditions. As the forward voltage drop of thyristors is slightly higher than the forward voltage drop of diodes, losses are slightly increased.

B.4.3 Active infeed converter

B.4.3.1 Active infeed converter with high switching frequency

The behaviour of active infeed converters (AIC) is described in detail in IEC/TS 62578. In contrast to the diode rectifier, this type of inverter is able to regenerate energy from the load to the mains. In regenerative applications, this feature can lead to a significant improvement of energy efficiency. Besides regeneration, this technology offers further advantages like the possibility of mains harmonics compensation, reactive power compensation and stabilized DC link voltage.

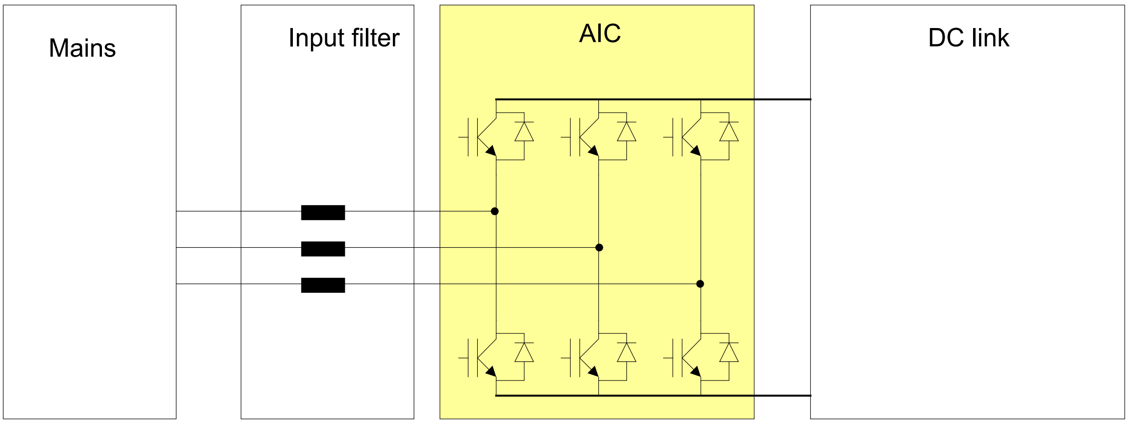


Figure B.5 — PDS with a standard AIC input converter

Standard active infeed converters operate with an IGBT bridge at their line infeed. The semiconductor switches operate at high switching frequency, enabling the converter to consume nearly sinusoidal current from the mains, with a controllable phase angle between line voltage and line current. Reactive power and harmonic currents are reduced to a minimum, minimising losses in the mains as a consequence.

However, the semiconductors create additional switching losses due to their high switching frequency and the topology also requires the use of a choke or higher order filter, which also create losses. Furthermore, the DC link voltage in AIC converters with high switching frequency is higher than the DC link voltage in passive infeed converters, leading to increased DC link and standby losses.

Single phase power factor correction (PFC) circuits show a very similar behaviour to standard active infeed converters. They are as well able to produce a nearly sinusoidal input current with an optimum phase angle, while requiring a line choke and creating additional switching losses. Main difference is their missing capability to regenerate energy to the mains.

B.4.3.2 Active infeed converter with fundamental switching frequency

In a special type of three phase active infeed converters, the line side IGBTs are operated with the switching frequency of the mains only. Due to this operating mode, the fundamental frequency front end AIC (F3E-AIC) reduces its losses to the value of the diode rectifier, while maintaining the feature to feed back energy from the load to the mains. Furthermore, the topology does not generate an increased DC link voltage. Like a diode rectifier described in B.4.2, this topology can be operated with or without line choke.

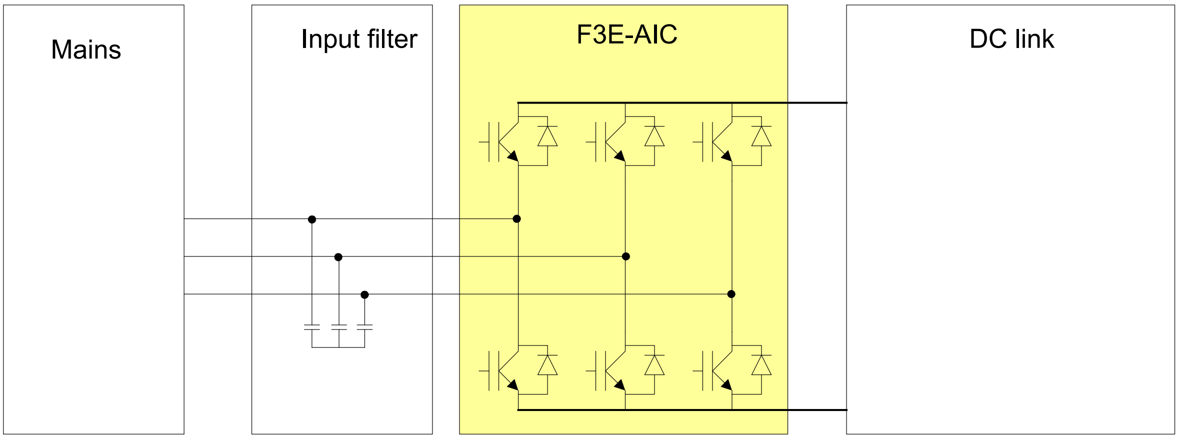


Figure B.6 — PDS with a F3E-AIC input converter without line choke

Due to these features, the energy efficiency of a PDS with this type of input converter is very high.

B.4.4 Power factor of the input converter

The power factor λ of the input current is defined as the ratio of the active input power to the apparent input power of the CDM. At sinusoidal input voltage, it depends on the current waveshape.

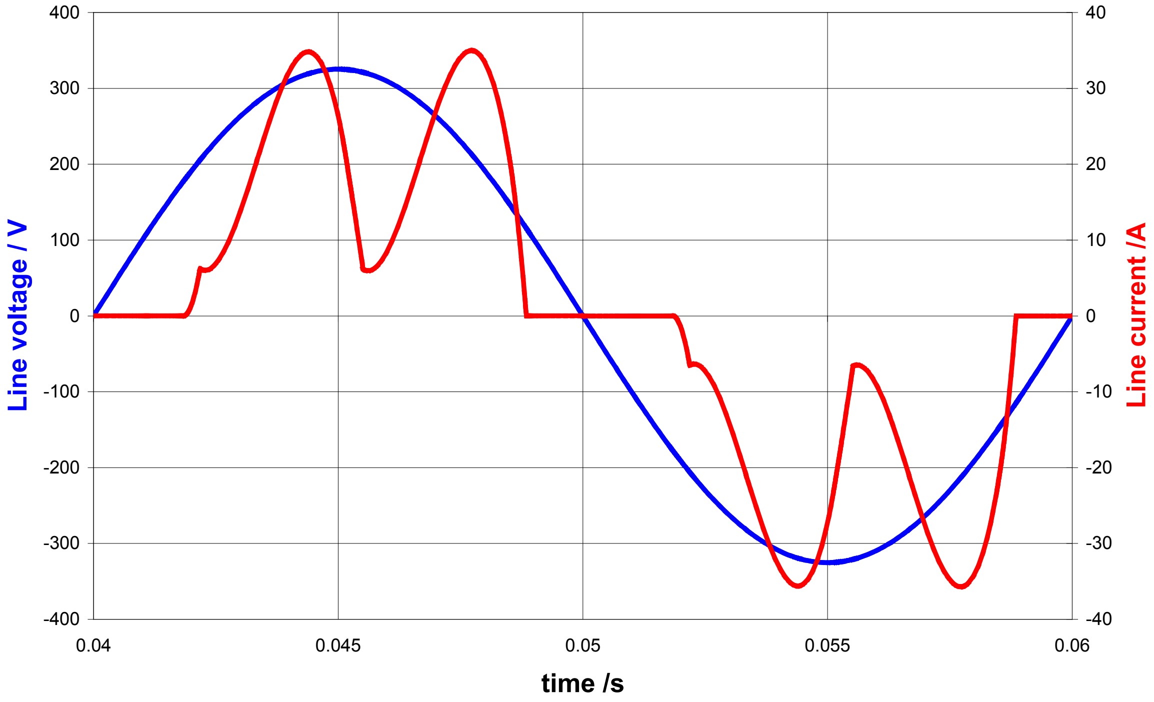


Figure B.7 — Typical waveform of a diode rectifier line current

If the CDM is equipped with a large DC link capacitor, decreasing the size of the input chokes will lead to a more peaky waveform of the input current. Consequently, the value of λ will decrease.

If the DC link capacitor is reduced to a very small value, the current current tends to a block shape waveform.

More information on input converter topologies is given in IEC/TS 62578. For the different topologies, the following typical values of λ apply:

Table B.1 — Typical values of λ for different input converter topologies

Input converter topology	Value of λ
Large DC link capacitor with 0,5 % input choke	0,6
Large DC link capacitor with 4 % input choke	0,7
Small DC link capacitor according to IEC/TS 62578	0,9
Active infeed converter with high switching frequency	1,0

B.5 DC link

The DC link of voltage source PDS consists of a DC link capacitor. This capacitor usually contains a large number of electrolytic capacitors. For a 400V three phase power supply system, the voltage in the DC link is usually higher than the voltage capability of a single commercially available electrolytic capacitor. For this reason, capacitors have to be connected in series in the DC link.

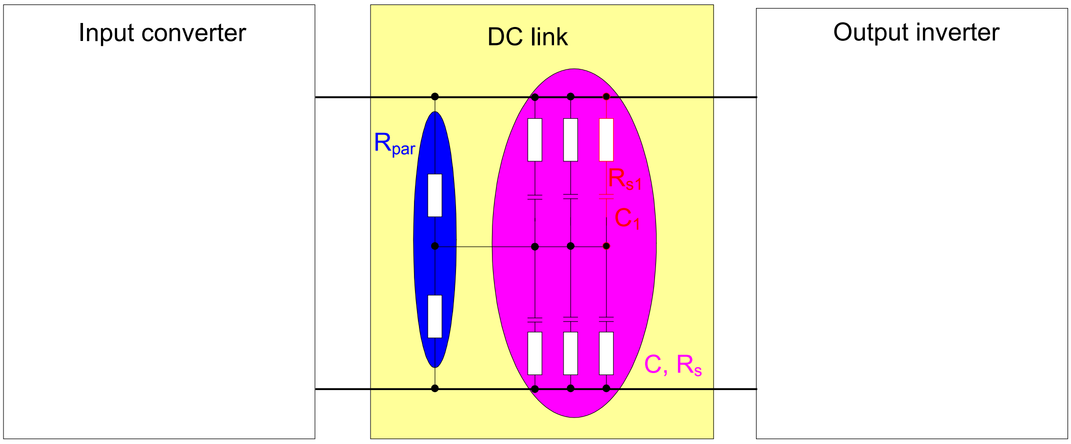


Figure B.8 — DC link circuit

In order to ensure proper voltage sharing of the electrolytic capacitors, resistors are required in parallel to the capacitors. The resulting equivalent resistor R generates one part of the energy losses in the DC link. In the mathematical model, those are taken into account in the first term of Formula (13). As each DC link capacitor requires a certain amount of parallel resistance for symmetrizing, this part of the DC link losses is proportional to the rated CDM output current. Furthermore, it is proportional to the square of the actual DC link voltage. The parameter $k1_{DC\_link}$ can be calculated by

$$k1_{DC\_link} = \frac{1}{R_{par} \cdot I_{r,out}} \tag{B.3}$$

The second part of the losses in the DC link is generated by the (equivalent) series resistance R_{s1} inside the capacitors. The losses appear mainly with six times the fundamental frequency of the mains and are proportional to the square of the input current of the rectifier. The parameter $k2_{DC\_link}$ can be calculated with the following steps:

1) The losses of a capacitor are usually specified in the datasheet with the loss factor tanδ at line frequency $\omega/2\pi$ (50Hz or 60Hz). The equivalent series resistor R_{s1} of one capacitor can be calculated by:

$$R_{s1} = C_1 \cdot \omega \cdot \tan\delta \tag{B.4}$$

2) The overall resulting resistor R_s of the complete DC link capacitor array C can be calculated according to the series and parallel connection of individual capacitors C_1.

3) The paramemter $k2_{DC\_link}$ can be calculated by

$$k2_{DC\_link} = R_s \cdot I_{r,out} \tag{B.5}$$

DC chokes may be used in the DC link. If these chokes are used, they usually replace AC line harmonics chokes in the input filter. As far as energy efficiency of the system and investment cost are concerned, DC chokes and AC chokes are in the same order of magnitude.

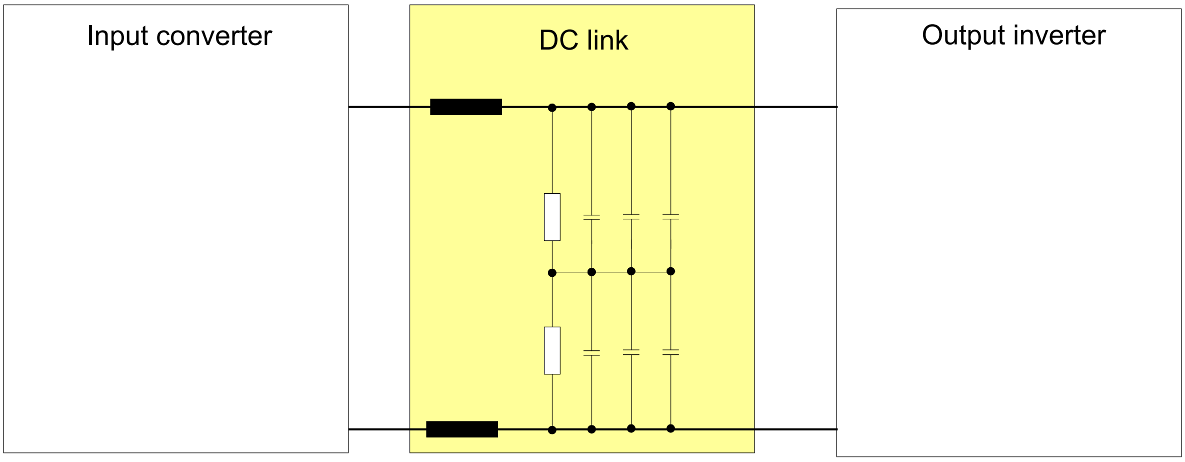


Figure B.9 — DC link circuit with additional DC chokes

In some BDM types, the amount of capacitance in the DC link is rather small. In this case, it is possible to use capacitors with a higher voltage withstand capability, parallel resistors are not required in that case, improving the overall energy efficiency of the system.

B.6 Output inverter

Output inverters in voltage source PDS usually consist of a three phase inverter bridge. By switching the semiconductors with a high frequency according to a pulse width modulated (PWM) control scheme, the speed of the motor at the output can be controlled to the desired value.

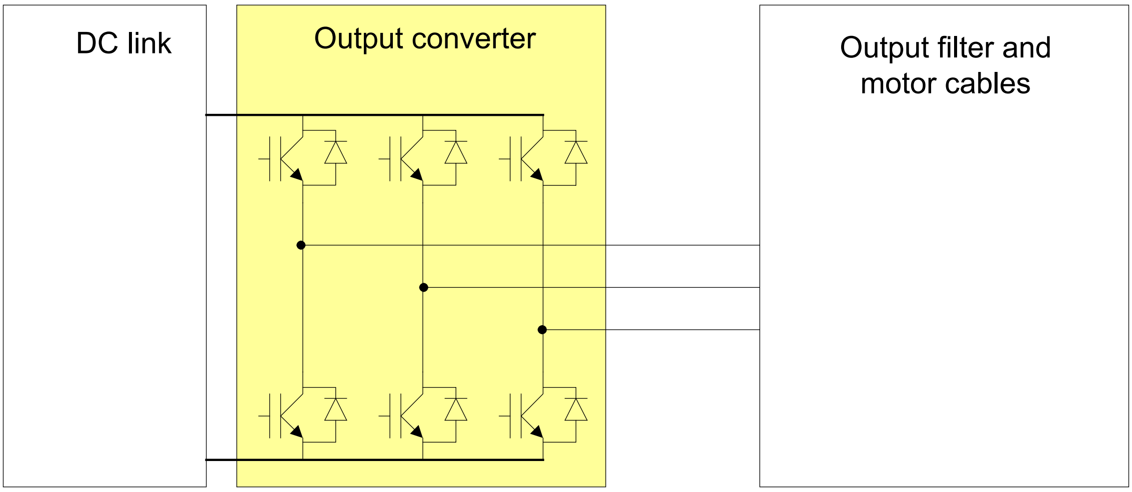


Figure B.10 — Output inverter of the PDS

Losses in the output inverter are generated by the on-state losses and the switching losses of the semiconductors. Both types of losses are reduced by continuous technological improvements in semiconductor development, either by improving the device structure or by using new semiconductor materials.

From the user’s point of view, losses in the output inverter can be influenced by the switching frequency. Reduced switching frequency leads to lower losses in the output inverter. A lower switching frequency, however, increases losses in the motor and in optional output filter circuits. For an optimized energy efficient solution, the combination of all those subsystems has to be investigated, see Figure 14.

B.7 Output filter and motor cables

B.7.1 General

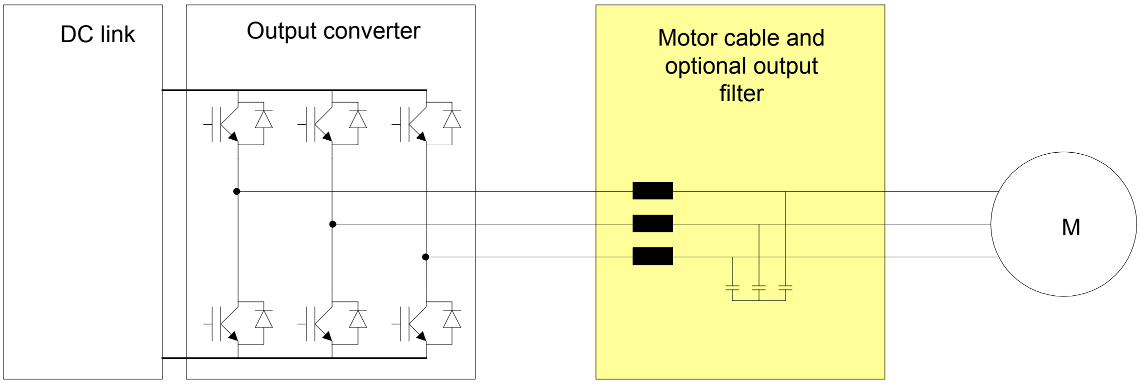


Figure B.11 — Motor cable and optional output filter of the PDS

The output inverter usually operates its semiconductor switches with high switching speed to minimise switching losses. If no output filters are used, overvoltage spikes due to reflexion of the voltage waveform can be observed at the motor terminals, stressing the motor insulation with twice the DC link voltage. This phenomenon can be observed if the length of the motor cable is longer than the critical length, which can be calculated as follows:

$$l_{crit} \geq \frac{v \cdot t_r}{2} \tag{B.6}$$

For a typical rise time of t_r = 200ns and a typical speed of the voltage wave of v = 150 m/µs the critical length of the motor cable is l_{crit} = 15m.

These voltage spikes lead to an increased stress of the motor insulation. However, their effect on losses is negligible.

In some cases, output filters are used, mainly to reduce the stress on the insulation of the motor and to increase the motor cable length. Different kinds of output filters are known, their effect on efficiency will be described.

B.7.2 Sine wave filters

Sine wave filters are designed to filter out the switching frequency of the inverter. They usually include at least one inductor and one capacitor, forming a second order filter for the output voltage of the inverter. The resonance frequency of a sine wave filter is chosen to be lower than the switching frequency of the inverter.

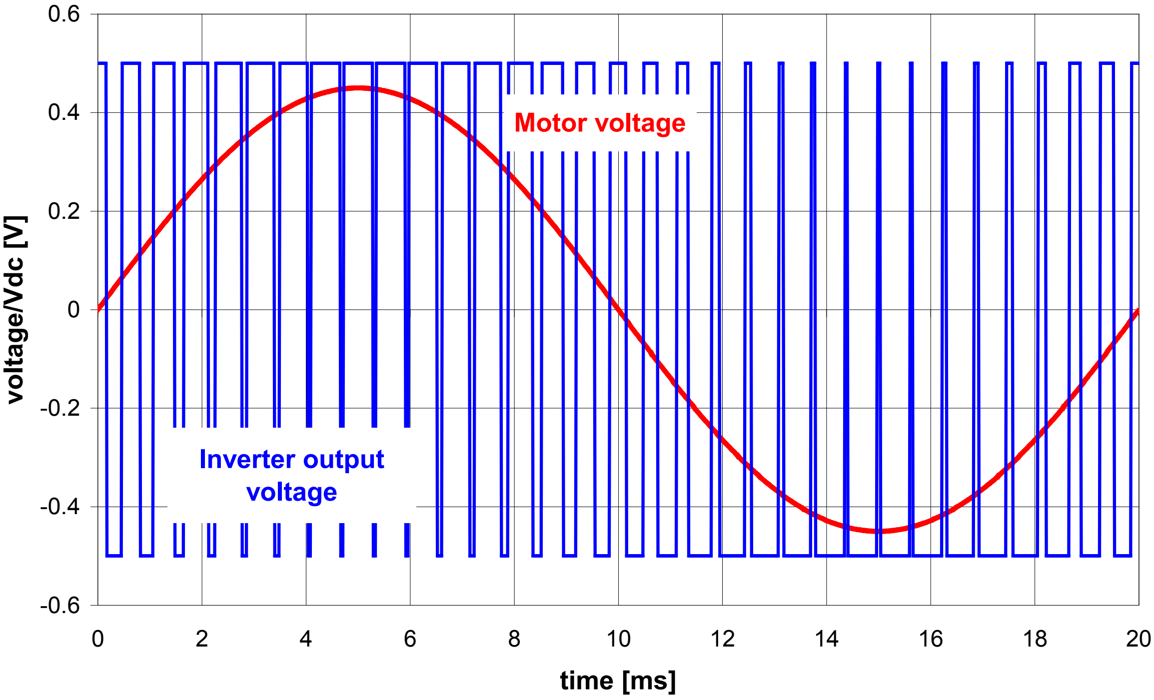


Figure B.12 — Typical waveform of inverter output voltage and motor voltage when using a sine wave output filter

When operating at an inverter without sine wave filter, the motor will show additional losses due to high frequency ripple currents. These additional losses are described in CLC/TS 60034-25. With a sine wave filter, these additional losses can be largely reduced.

However, the sine wave filter itself will show some losses, mainly due to the copper and iron losses in the filter inductor. These losses are known to be less than 0,5 % of the rated inverter power for high power sizes and may be up to 8 % of the rated inverter power for low power sizes at rated motor speed. At lower motor speed, these losses are even lower.

However, this type of filter produces a small volt-drop at power frequency and there may be a reduction in the available control bandwidth, particularly if the PWM frequency is low. Therefore, it is sometimes not possible to use this type of filter.

B.7.3 dV/dt filters and motor chokes

dV/dt filters are used to increase the rise time of the motor voltage in order to reduce the stress on the motor insulation. They show basically the same topology as sine wave filters. In contrast to those, their resonance frequency is chosen far higher than the switching frequency, resulting in considerably smaller components. However, the motor voltage remains similar to the waveform of the inverter output voltage shown in Figure B.12. Losses in the motor are not affected by the dV/dt filter.

Losses in the dV/dt filter itself are proportional to the switching frequency of the inverter. The losses in the dV/dt filter might be up to 1 % of the rated PDS power. At a switching frequency of 500Hz, the losses in the dV/dt filter are typically less than 0,25 % of the rated PDS power. Exact losses have to be determined at the applied switching frequency.

For PDS with higher switching frequency, motor chokes may be used instead of dV/dt filters to reduce the stress on the motor insulation. Losses generated by these chokes are comparable to losses of a sine wave filter. However, the reduction of the stress on the insulation is not as effective as with filter solutions. Motor losses are not affected either.

B.7.4 High frequency EMI motor filters

High frequency EMI motor filters, similar but not identical to those described in B.3.1, may be used at the inverter output terminals as well. Their influence is similar to the line side EMI filters.

B.7.5 Motor cables

Motor cables connect the CDM with the motor. The resistive behaviour of the motor cables causes losses that should be considered for long motor cables. As the length of the motor cables is different for each installation, these losses cannot be given as an attribute of a PDS, but have to be assessed in every individual installation. As a rule of thumb, motor cable losses can be neglected as long as their length is below 25m. Most of the losses are due to the fundamental motor current, the influence of the high frequency current can be neglected. If single wire cables with individual shielding are used instead of three wire cables, current will cause additionally losses in the cable shields.

B.8 Motor

A method to evaluate losses generated in the motor, when operated either with a sinusoidal waveform or with a pulsed waveform from an inverter, is described in EN 60034-2-1 and IEC/TS 60034-2-3. Auxiliary fans and brakes are a part of the motor system.

B.9 Mechanical load

Losses in the load strongly depend on the kind of application the PDS is used for. The loss saving potential by running the load in an energetically optimized way is far greater than the losses of the PDS and shall therefore be the major issue when designing an application to minimum losses. This issue is adressed in Annex A.

B.10 Control and standby losses

Control losses usually do not depend significantly on the rated CDM power. For this type of losses, it is more important to evaluate the automation system as a whole and the control functions of the PDS, such as bus communication and driving additional equipment like e.g. relays, position sensors or motor brakes. For very low power PDS (< 500 W), this portion of the losses might be in the same order of magnitude as the power losses, whereas it is getting less and less important for higher rated PDS power.

Besides the losses in the control part of the CDM itself, there are also losses created in the switch mode power supplies of the CDM, supplying e.g. a fan as a major consumer, in case of forced air cooling. These losses are mainly independent of the CDM and are therefore regarded like control losses as well.

The control and standby losses $P_{L,control}$ are generated when the PDS is powered up, but the motor is not energized. They are typically one 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 application in terms of wake-up time and communication.

B.11 Cooling losses

B.11.1 Primary cooling losses

The primary cooling of the components illustrated in Figure 11 is mainly done by the primary cooling (fan or liquid cooling) integrated in the BDM/CDM/PDS. The cooling might be temperature dependant (ON/OFF or PWM controlled) or might be an uncontrolled cooling system.

B.11.2 Secondary cooling losses

Besides the fact that the all components shown in Figure B.1 create losses, these losses have to be cooled by a secondary cooling system in many applications. It is depending on the application itself which losses have to be cooled by a secondary cooling system.

A typical secondary cooling system is an air conditioning system, keeping the temperature of targeted room below a certain value. All losses generated in this room have to be actively cooled by the secondary system, including e.g. losses of a control system. As a minimum, the secondary cooling system has to cover the losses of the CDM itself. In this case, the power consumption of a typical secondary cooling system is in the range of 20 % of the CDM losses.

However, in some applications, the motor and the load machine require cooling as well. These losses have to be taken into account by the overall system designer and are not in the scope of this standard.

Annex C
(informative)

Converter topology

C.1 General

In the vast majority of applications, CDM topologies described in Annex B can be found. This is especially true for operation of the CDM at a line voltage up to 1000Vac. In this case, the mathematical models described in Clause 5 describe the losses of a CDM or a PDS with sufficient accuracy.

However, in some cases, different converter topologies can be found. Their impact on losses is described in a qualitative manner in this informative annex.

C.2 Voltage source output inverter topologies different from those mathematically described in 5.2.2

The mathematical model in 5.2.2 describes the losses of a 2 level voltage source inverter. In some applications, higher level topologies are used, mainly in medium voltage CDM's. The simplest solution in this case is a three level inverter, but also multi-level topologies are used in rare cases.

Depending on the switching frequency and the voltage rating, multilevel topologies offer the possibility to reduce the losses of a CDM. Furthermore, they offer the possibility to reduce the losses in the motor, because the harmonics in the motor current are lower for the same switching frequency of the semiconductor devices. Consequently, calculating the inverter losses with the mathematical model given in 5.2.2 will result in higher losses than in a practical application and will therefore deliver results on the safe side, as far as the evaluation of the IE class is concerned.

As the mathematical calculation of inverter losses is significantly more complex than for a 2 level topology, it is not included in the first edition of this standard.

C.3 Voltage source input converter topologies different from those mathematically described in 5.2.3

If the input converter is a multilevel active infeed converter, the same considerations as in C.2 apply.

For passive input converters, Figure B.4 shows a six pulse infeed converter and Figure B.7 shows a typical waveform for this topology. In some applications, which are designed for very low harmonic input currents, 12-pulse, 18-pulse or 24-pulse infeed converters are used. In this case, the input converter current stays very similar to the waveform shown in Figure B.7, consequently, the mathematical model described in 5.2.3 can be used for all passive infeed topologies.

Other infeed converter topologies, e.g. non-regenerative PFC topologies, are rarely to be found and will be described in a future edition of this standard.

C.4 CDM topologies different from voltage source type

CDM topologies different from voltage source type, like current source inverters or direct converters, can be found in a small number of applications, mainly in the high power range above 1MW and in the high voltage range above 1000Vac. The calculation of losses for these topologies is quite different from the mathematical model given in 5.1. A mathematical model for these topologies will be given in a future edition of this standard, if this is assumed to be required. In this edition, a qualitative statement will be given only.

Current source CDM's usually show higher losses compared to a voltage source CDM due to the following reasons:

- Current source inverters require power semiconductor devices with reverse blocking capability. These power semiconductors usually show a higher forward voltage drop compared to asymmetrically blocking power semiconductors. Consequently, their conduction losses are usually higher.
- In the DC link, the parallel capacitor shown in Figure B.8 is replaced by a series inductor. The losses in this series DC link inductor are usually higher than the losses of a parallel DC link capacitor.

Besides higher losses in the CDM, however, current source CDM's produce a voltage waveform at their output terminals which is much closer to a sinusoidal waveform than the voltage output waveform of a voltage source CDM. Consequently, the harmonic losses in the motor are expected to be lower. In the overall PDS, the losses are expected to be similar.

Direct converters offer the possibility to directly connect each input phase to each output phase of the CDM. For this type of CDM, two topologies are known:

1) Matrix converters use power semiconductor devices similar to voltage source output inverters, operating at similar switching frequency. Losses in this type of CDM are reported to be similar to voltage source CDM's, though their mathematical model is quite different. Matrix converters can only be found very rarely in applications due to several reasons, there are no indications that this situation will change in the near future.

2) Thyristor cyclo converters are used for very high power ratings in the range above 10MW, mainly in applications with a low output frequency of the CDM. The thyristors are operated with a very low switching frequency which is in similar to the line frequency, and the thyristors show a comparatively low forward voltage drop. Consequently, the losses of this type of CDM's are comparatively low. On the other hand, the losses in the motor and the mains are higher than for standard voltage source CDM's, as the voltage waveform shows high harmonics.

Annex D
(informative)

Basic Torque and Power vs. speed profiles, operating points over time

D.1 General

NOTE This Annex D might be moved to a future document xxx-1.

To judge an application concerning energy efficiency all components of the application have to be taken into account. Speed regulation by using a power drive system (PDS) is advantageous in a plurality of cases, but on the other hand it also creates additional losses.

The energy savings that can be achieved are very often depending on the operating point *OP*. Therefore it is necessary to have information about the extended product and its duty to decide.

Two extended product-relative characteristics are particularly useful for describing the extended product and the way it is operated:

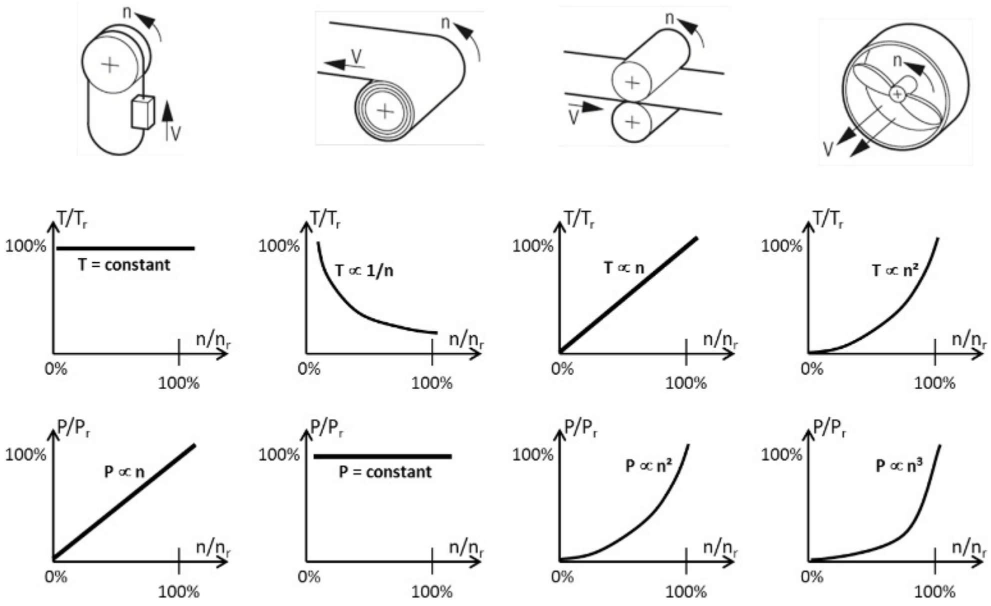
- **The torque and power versus speed profile.** This curve describes how the torque required by a machine depends on its speed. It essentially depends on the type of machine (motor, pump, fan…).
- **Operating points over time.** This graph describes the various power levels required by the extended product, including standby, and the fraction of time during which the machine is operated at these levels. The duty profile essentially depends on the sizing of the motor and on how the extended product is operated in practice.

These two characteristics can be used as input data to compare potential control solutions in terms of energy efficiency.

D.2 Basic Torque and Power vs. Speed Profile

The torque or power versus speed profile describes how the torque T or power P required by the driven load varies with its speed n. The power is also the product of torque and speed.

Most of the existing loads can be categorized into one of the basic torque and power vs speed profiles shown below.



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

Figure D.1 – Typical basic torque and power vs. speed profiles

D.3 Operating points over time

The desired behaviour of the extended product, as well as the characteristics of the motor, defines one or several operating points at which the motor will have to be operated.

Depending on these points the motor may not be running at rated output power all the time. Part load in the sense of this standard is a situation where the system requires reduced torque and/or speed compared to the rated values.

The efficiency of an extended product strongly depends on the load level. Furthermore, stand-by (SB) losses of soft starters and VSDs have to be taken into account. They are present in periods where the power part is disabled but the control is still supplied. Stand by losses are losses generated by e.g. the power supply of the control part.

Therefore, to estimate the efficiency of an extended product and compare several potential control solutions, it is essential to know which levels of mechanical and electrical power are needed by the extended product and in which time fraction. This is the purpose of the operating points over time.

D.4 Definition of the operating points over time

D.4.1 General

”Operating points over time” is a graph describing the different levels of mechanical power required by the extended product, and the time during which the extended product is operated at each of these points.

- The Operating points OP_i on the horizontal axis should reflect typical points for that certain extended product. One point shall be zero speed / zero torque to account for the standby losses P_{SB}.

  For some extended products, the operating points may be expressed using another quantity that makes sense for the extended product e.g. a power, a flow, etc.

In case the loss values for these points are not given by the manufacturer they can be calculated (see Annex G).

- The time may be expressed in hours per unit of time (day, year), or in fraction of the total runtime.

An example of operating points over time is shown in Figure D.2:

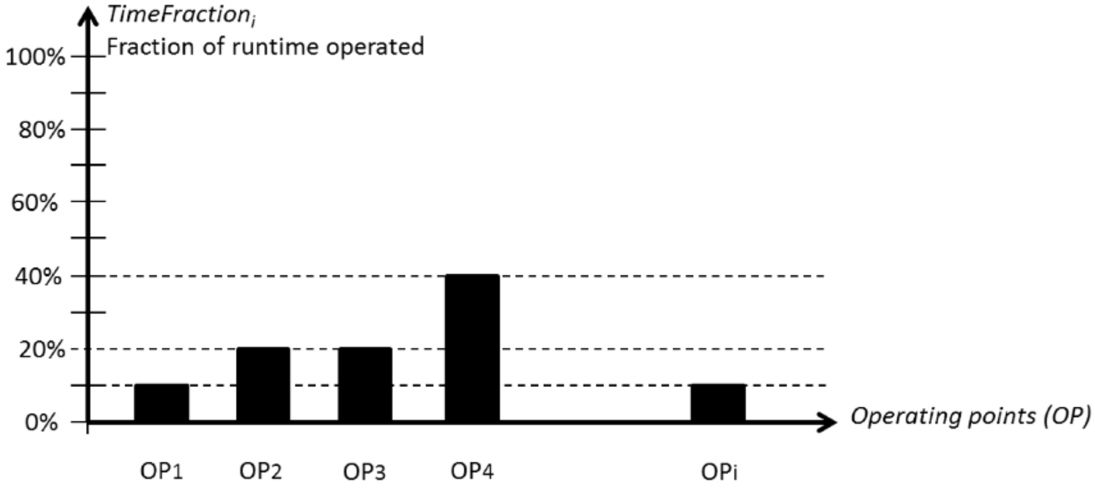


Figure D.2 — Example of operating points over time

D.4.2 Calculation of the energy consumption based on the duty profile

The duty profile describes the requirements of the extended product in terms of mechanical power. For each operating Point OPi, the electrical power P_i that shall be supplied by the mains depends on the mechanical power and the overall extended product losses (or equivalently its efficiency) at this level. The latter depends on the control strategy chosen for the extended product and can be computed.

The weighted average electrical power $P_{Electrical}$ required to run the extended product as desired is:

$$P_{Electrical} = \sum_{i=1}^{n} \left(Timefraction_i \cdot P_i\right) \tag{D.1}$$

The weighted average electrical power is directly relative to the electrical energy consumption (in e.g. kW.h) required by the extended product during a certain runtime period:

$$E_{Electrical} = P_{Electrical} \cdot Runtime \tag{D.2}$$

The weighted average electrical power (or equivalently electrical energy) can be computed for several potential control strategies suitable for the extended product (e.g. switchgear and VSD). The designer should then select the control strategy that yields the smallest weighted average electrical power.

Procedures for computing the losses at a certain operating point not included in datasheets are described in Annex G.

D.4.3 Example of loss calculation for different operating points over time

A pumping application with a 30 kW motor is working at three different operating points: 0 % flow (standby), 50 % flow and 100 % flow. It has to be checked which configuration is the most efficient one. The calculation has to be done for two different duties.

- Configuration 1: single speed pump with IE3 motor and throttling valve;
- Configuration 2: multi speed pump with IE2 motor and variable speed drive.

Table D.1 — Duty cycles of the investigated examples

	100 % flow	50 % flow	0 % flow
Duty 1	85 %	5 %	10 %
Duty 2	20 %	70 %	10 %

Table D.2 — Losses in the specified operating points of Configuration 1

Loss calculation configuration 1	100 % flow	50 % flow	0 % flow (standby)
$P_{\text{L pump1}}$ Losses of the pump system including valve in configuration 1	5,4 kW ①	9,36 kW ①	0 kW
$P_{\text{LT Motor1}}$ Losses of the motor in configuration 1	2,051 kW ②	1,5 kW ③	0 kW
$P_{\text{L Starter1}}$	0,03 kW ④	0,03 kW ④	0 kW
$P_{\text{L Total1}}$	**7,35 kW**	**10,89 kW**	**0 kW**

① calculated from the efficiency of a pump system with valve at different flow rates

② losses calculated with a motor efficiency according to IEC 60034-30 for a 30 kW 4-pole IE3 motor

③ Losses from 100 % flow multiplied with a factor coming from Figure F.1 (0,72/0,92) at 100 % speed (n_N)

④ 0,1 % of motor power according to Clause 6

Table D.3 — Losses in the specified operating points of configuration 2

Loss calculation configuration 2	100 % flow (100 % speed, 100 % load)	50 % flow (50 % speed, 25 % load)	0 % flow (standby)
$P_{\text{L pump2}}$ Losses of the pump system in configuration 2	5,4 kW ⑤	0,79 kW ⑤	0 kW
$P_{\text{LT Motor2}}$ Losses of the motor in configuration 2	2,76 kW ⑥	0,87 kW ⑦	0 kW
$P_{\text{L CDM2}}$	1,03 kW ⑧	0,34 kW ⑧	0,05 kW
$\boldsymbol{P}_{\textbf{L Total2}}$	**9,19 kW**	**2,00 kW**	**0,05 kW**

⑤ Calculated from the efficiency of a pump system with variable speed at different flow rates

⑥ 9,2 % of motor power according to Figure F.2

⑦ 2,9 % of motor power according to Figure F.2 at 50 % speed and 25 % torque

⑧ Losses of RCDM according to Table A.1

Duty 1

Configuration 1

$$P_{L,Conf1} = 0{,}1 \cdot P_{L,Total1\_0} + 0{,}05 \cdot P_{L,Total1\_50} + 0{,}85 \cdot P_{L,Total1\_100}$$
$$= 0{,}1 \cdot 0kW + 0{,}05 \cdot 10{,}89kW + 0{,}85 \cdot 7{,}35kW = 6{,}79kW \qquad \text{(D.3)}$$

Configuration 2

$$P_{L,Conf2} = 0{,}1 \cdot P_{L,Total2\_0} + 0{,}05 \cdot P_{L,Total2\_50} + 0{,}85 \cdot P_{L,Total2\_100}$$
$$= 0{,}1 \cdot 0{,}05kW + 0{,}05 \cdot 2{,}00kW + 0{,}85 \cdot 9{,}19kW = 7{,}92kW \qquad \text{(D.4)}$$

Result: Configuration 1 has less losses compared to Configuration 2 with Duty 1.

Explanation: The pump is running at 100 % flow for 85 % of the time where the variable speed drive brings additional losses compared to a motor starter. Also the losses inside the motor increase. The additional losses in the throttling valve at 50 % flow are of minor importance because they are used in 5 % of the time only.

Duty 2

Configuration 1:

$$P_{L,Conf1} = 0{,}1 \cdot P_{L,Total1\_0} + 0{,}7 \cdot P_{L,Total1\_50} + 0{,}2 \cdot P_{L,Total1\_100}$$
$$= 0{,}1 \cdot 0kW + 0{,}7 \cdot 10{,}89kW + 0{,}2 \cdot 7{,}35kW = 9{,}09kW \tag{D.5}$$

Configuration 2:

$$P_{L,Conf2} = 0{,}1 \cdot P_{L,Total2\_0} + 0{,}7 \cdot P_{L,Total2\_50} + 0{,}2 \cdot P_{L,Total2\_100}$$
$$= 0{,}1 \cdot 0{,}05kW + 0{,}7 \cdot 2{,}00kW + 0{,}2 \cdot 9{,}19kW = 3{,}24kW \tag{D.6}$$

Result: Configuration 1 has more losses compared to Configuration 2 with Duty 2.

Explanation: The pump is running at 50 % flow for 70 % of the time where the throttling valve has many losses. In this case the additional losses of the variable speed drive at 100 % flow in 20 % of the time are of minor importance.

Annex E
(informative)

Typical standardized servo application

E.1 General

In a servo application, a PDS is operated in a different way compared to general purpose applications which are in the main focus of this document. For general purpose applications, rated speed and rated torque define the characteristic operating point.

In contrast to this, servo applications usually use a PDS in overload condition for a certain time, followed by another operating phase with low torque or even standstill. The rating of a CDM or a motor for a servo application is consequently chosen according to the maximum instantaneously allowed torque at a defined speed. An example for this is given in Figure E.1.

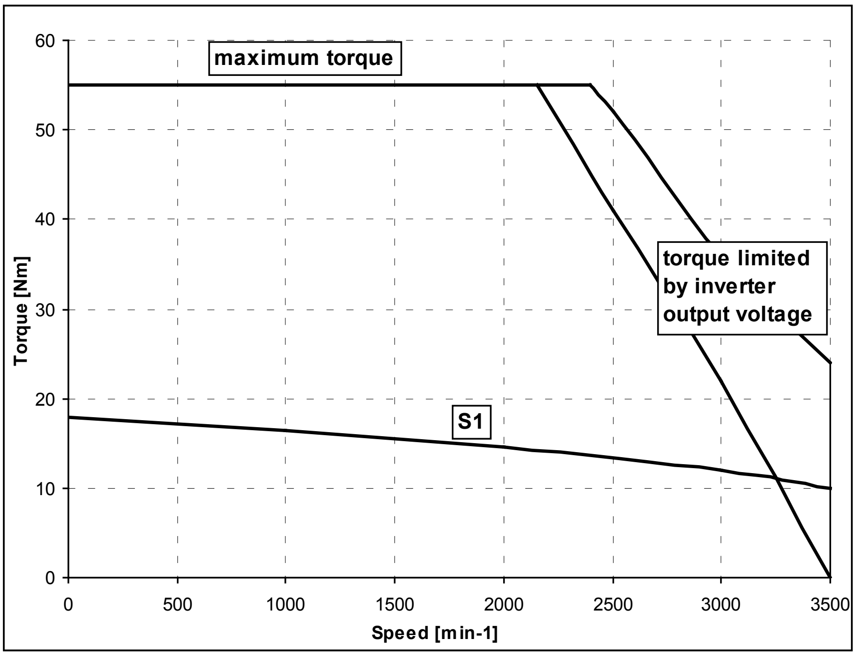


Figure E.1 — Sample of a typical torque - speed characteristic

S1 according to IEC 60034 is the limiting curve for continuous operation. Rated speed is 3 000 min^{-1}. Rated torque is the continuous torque at rated speed, which in this case is 12 Nm. For a general purpose PDS, this would result in a square operating area limited by these two values. A servo PDS, however, defines the permissible torque as a function of speed, resulting in the shown curve for S1 with different inverter output voltages result in different torque limiting curves. An example for the maximum instantaneously allowed torque as a function of the speed is shown in the second graph in Figure E.1.

A typical operating cycle for a servomotor includes an acceleration /starting phase up to maximum speed, a stationary processing phase with constant load and an electric braking phase down to zero speed. After these three phases a current- and load free phase at standstill follows (similar to duty type S5– Intermittent periodic duty with electric braking in EN 60034-1). To prevent an overheating of the motor, the complete cycle has to be designed correctly regarding the duration of the different phases. The thermal behaviour is not relevant for energy efficiency calculation, the influence is neglected.

The duty type S3 - Intermittent periodic duty from EN 60034-1 is not suitable because acceleration and braking phases and the parameter speed are not considered.

To calculate losses for a servo PDS in association with a typical operating cycle the following motor parameters are used.

Table E.1 — Parameters of an example servo motor

Parameter	Dimension unit	Value (sample)
Rated speed - n_r	min^{-1}	3 000
Rated torque - T_r	Nm	12
Stall torque - T_0	Nm	18
Voltage constant at 20 °C - k_E	V/1 000 min^{-1}	105
Rated efficiency – η_r	%	93 (at 3 000 min^{-1}, 12 Nm)
Moment of inertia – J_M	kgm^3	5,4 10^{-4}
Resistance Winding R_{phase}	Ω	0,324

E.2 Cycle

To define a suited cycle the maximum speed and the maximum torque for acceleration have to be defined. For a servo PDS, it makes sense to classify into high dynamic and medium dynamic applications.

Table E.2 — Typical operating cycles for a servo motor

	maximum speed n_{max}	maximum torque T_{max}
high dynamic application	75 % rated speed – 0,75 x n_r	3 x To
medium dynamic application	rated speed – n_r	2 x To

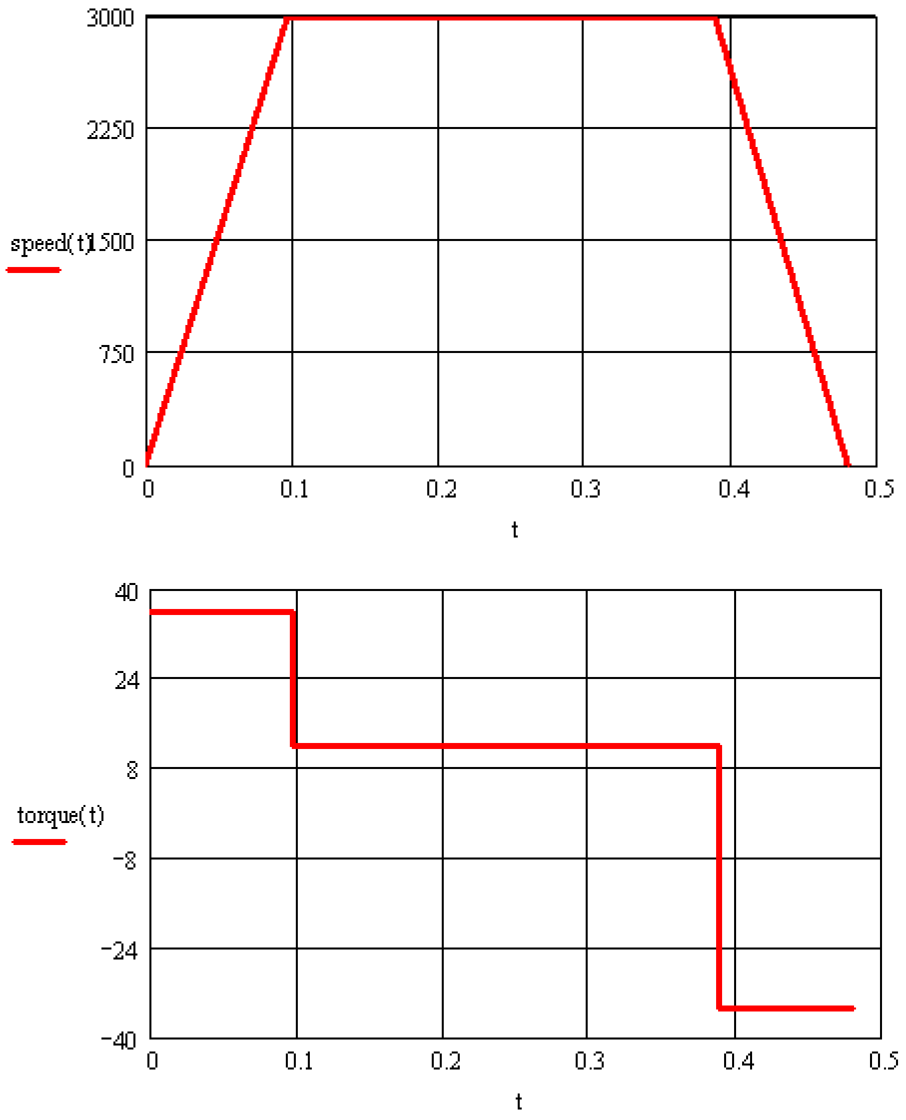


Figure E.2 — Speed and torque for a medium dynamic application cycle (sample)

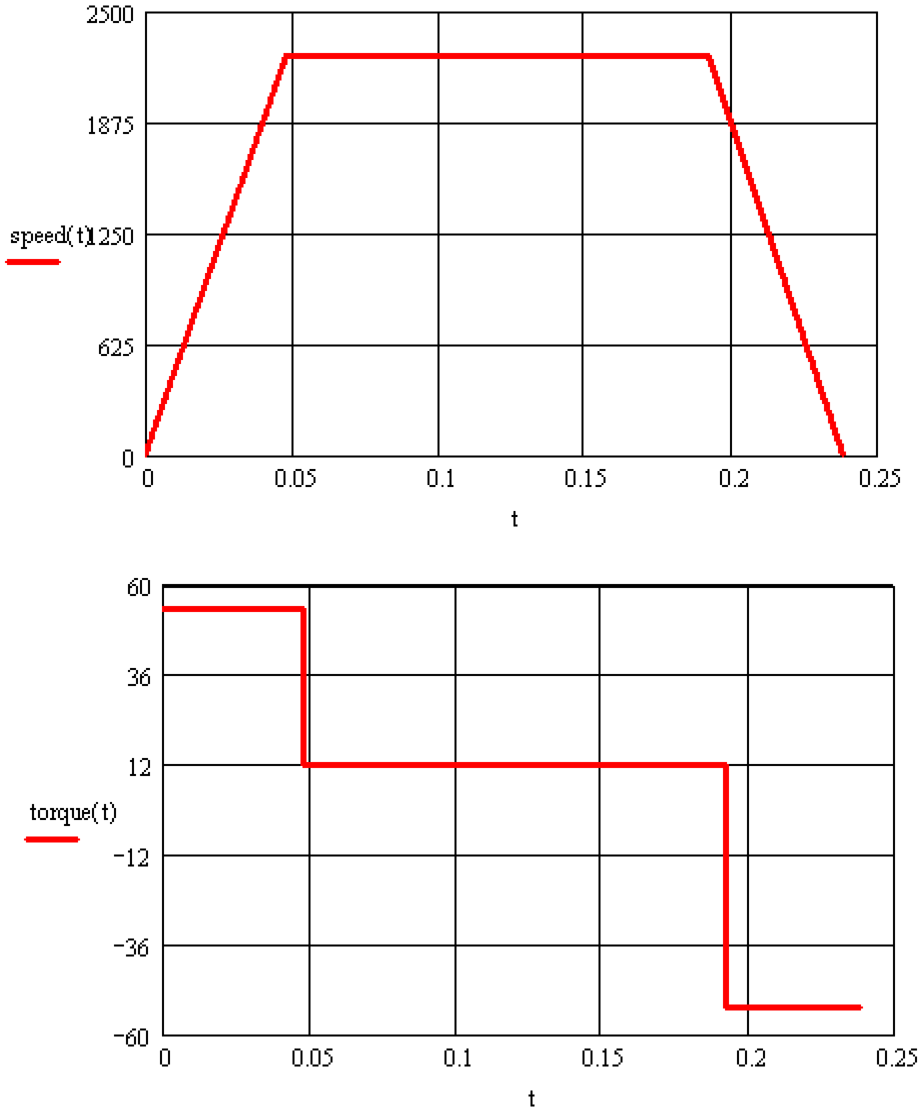


Figure E.3 — Speed and torque for a high dynamic application cycle (sample)

During acceleration time the acceleration torque T_a depends on the maximum torque Tmax and the friction torque T_{fr} . T_{fr} can be assumed to be 10 % of rated Torque (T_{fr} =0,1 T_r).

$$T_a = T_{\max} - T_{fr} \tag{E.1}$$

The run up time / acceleration time from zero speed to maximum speed is:

$$t_a = \frac{J_{res}\, 2\pi n_{\max}}{T_a} \tag{E.2}$$

J_{res} is the complete moment of inertia resulting from motor moment of inertia and the external moment of inertia, which can be assumed do be:

$$J_{res} = J_M + J_{ext} = 2\, J_M \tag{E.3}$$

The duration of stationary processing phase can be set to $t_{\mathrm{proc}} = 3\, t_{\mathrm{a}}$. The torque in this phase is set to rated torque Tr.

During braking time the braking torque T_{b} is depending on the maximum torque T_{max} and friction torque T_{fr}.

$$T_b = T_{\max} + T_{fr} \tag{E.4}$$

The braking time from maximum speed to zero speed is:

$$t_b = \frac{J_{res}\; 2\pi n_{\max}}{T_b} \tag{E.5}$$

E.3 Calculation of motor losses

For calculation off losses the temperature dependency is neglected. The temperature is assumed to be 20 °C.

The losses in the windings / copper losses:

$$P_{lCu}(t) = 3\,\frac{M^2(t)}{k_T^{\;2}}\, R_{phase} \tag{E.6}$$

k_T (in Nm/A) is the torque constant. $k_T = k_E\,\frac{3\sqrt{3}}{100\,\pi}$

The speed dependent losses at rated speed:

$$P_{n,r} = 2\pi n_r M_r \left(\frac{1}{\eta_r} - 1\right) - \frac{3T^2{}_r}{k^2{}_T} R_{phase} \tag{E.7}$$

The speed dependent losses, time dependent:

$$P_n(t) = P_{n,r}\,\frac{n^2(t)}{n_r^{\;2}} \tag{E.8}$$

For the medium dynamic application, the instantaneous losses result in:

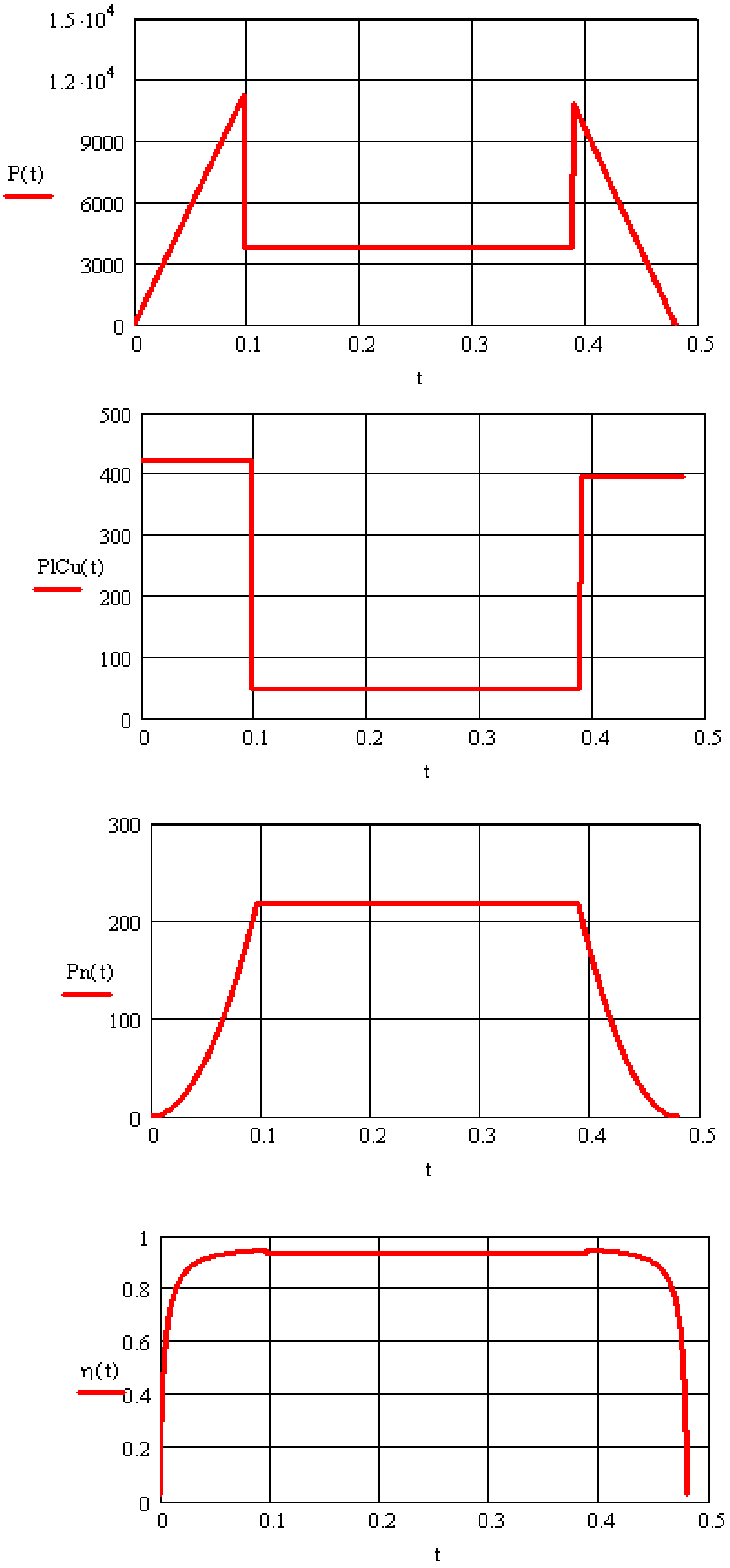


Figure E.4 — Graphic chart of power and losses for medium dynamic application

The overall losses in the complete cycle complete duration of the cycle can be calculated by integrating those graphs. The cycle time without the load free phase is:

$$t_{com} = t_a + t_{proc} + t_b \tag{E.9}$$

Windings and copper losses are:

$$P_{Cu} = \frac{1}{t_{com}} \cdot \int_0^{t_{com}} P_{lCu}(t)\, dt \tag{E.10}$$

Speed dependent losses are:

$$P_n = \frac{1}{t_{com}} \cdot \int_0^{t_{com}} P_n(t)\, dt \tag{E.11}$$

For the example shown above the resulting relative losses:

-	for high dynamic application are calculated to	11,7 %
-	and for medium dynamic application are calculated to	7,3 %

E.4 Losses of the servo CDM

For the servo CDM, the mathematical model given in 5.1 can be used as well. However, the data given in Table 2 and Table 3 are valid for asynchronous motors only. For synchronous motors, it can be assumed that the motor current is proportional to the torque and the phase angle is 0,9.

The mathematical model is suitable for calculating steady state operating points. In Figure E.2, a ramp up for the acceleration phase is given. The speed of the motor and consequently the output frequency of the CDM have an influence on the on state loss distribution between transistor and diode in the CDM and, as shown in Figure 12, the dependency of the overall CDM losses on this parameter can be approximated to be linear. Consequently, the relative output frequency of the CDM is approximated to be constant at half of the output frequency during the acceleration interval. The same assumption is used during braking.

With these assumptions, the losses in the CDM during the load cycle shown in Figure E.2 can be calculated by adding the losses in the three defined operating points during acceleration, steady state processing and braking according to Formula (D.1). An example for calculating the CDM losses at one single operating point is given in Annex G.

E.5 Losses of the servo PDS

Losses for the servo PDS can be calculated by adding the losses of the servo CDM and the losses of the servo motor for one given load cycle.

Annex F
(informative)

Additional information to 5.3

This Annex F gives an example how to determine the total losses of a motor driven by a converter using the method developed in 5.3 and tables with coefficients for on the market available 2- and 4-pole IE2 motors :

Formula (25) determined in 5.3.2.8 can be well approximated by a parabolic function,

either versus torque: where parameter is speed:

$$\frac{P_{LT,Mot}}{P_{r,M}} = A \cdot \left[\frac{T}{T_N}\right]^2 + B \cdot \left[\frac{T}{T_N}\right] + C \qquad \text{(F.1)}$$

or versus speed : where parameter is torque:

$$\frac{P_{LT,Mot}}{P_{r,M}} = A \cdot \left[\frac{n}{n_N}\right]^2 + B \cdot \left[\frac{n}{n_N}\right] + C \qquad \text{(F.2)}$$

where

$\frac{P_{LT,Mot}}{P_{r,M}}$	Total losses related to rated power stated on name plate
$\frac{T}{T_N}$	Torque related to rated motor torque
$\frac{n}{n_N}$	Speed related to rated speed of the motor

Figure F.1 and Figure F.2 below give an example for a motor 30 kW – 4 Pole.

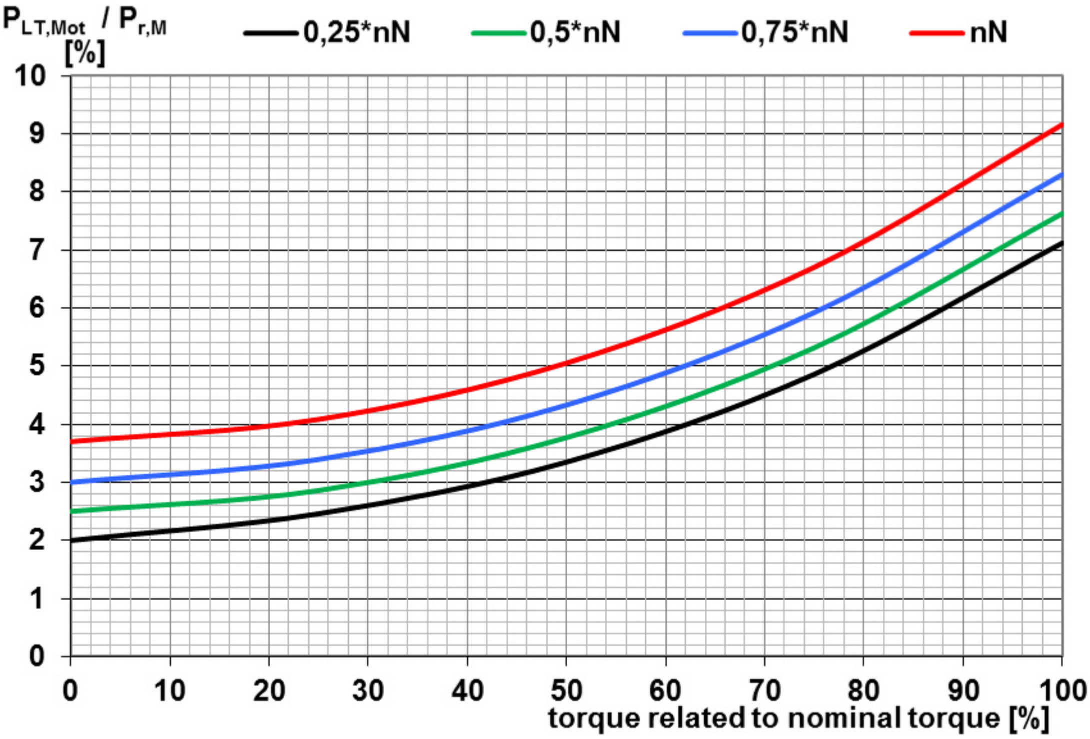


Figure F.1 — Relative losses versus relative torque, converter operation (parameter speed)

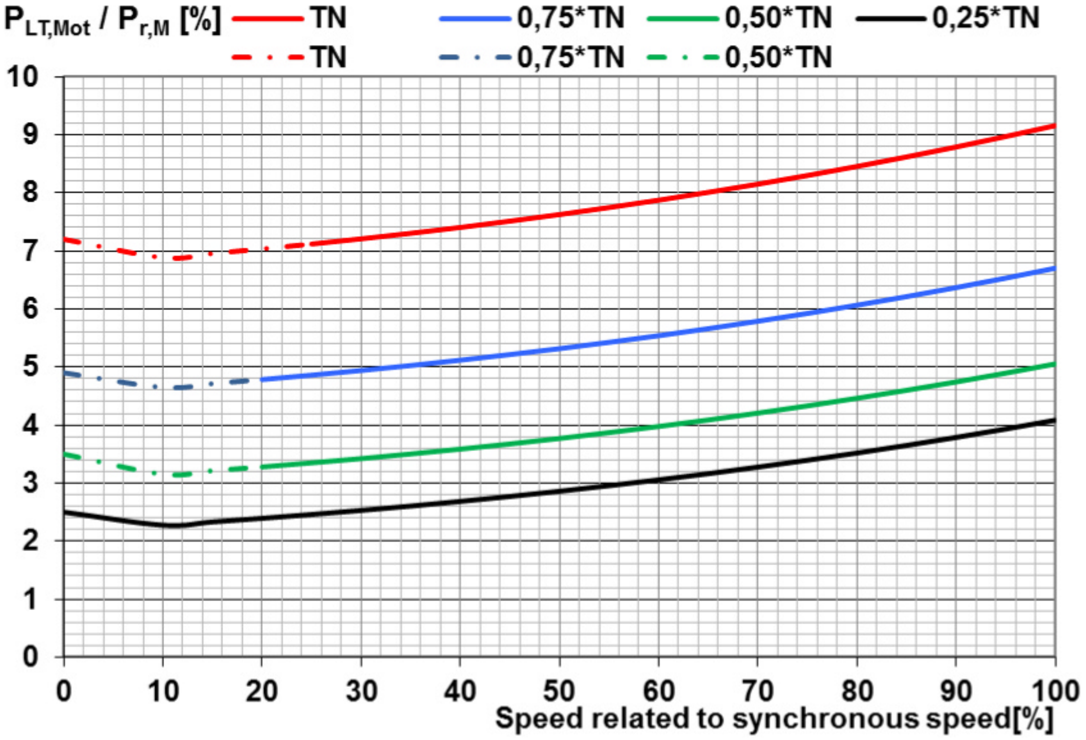


Figure F.2 — Relative losses versus relative speed, converter operation (parameter torque)

The resulting curves above approximated by a parabolic function, allow getting values for every desired point by interpolation between the 4 curves. See Figure F.3 below as an example with a fan / pump application. An extrapolation to torques below 25 % of nominal torque is also possible.

Load capacity of motor according to speed range requested has to be considered during the selection.

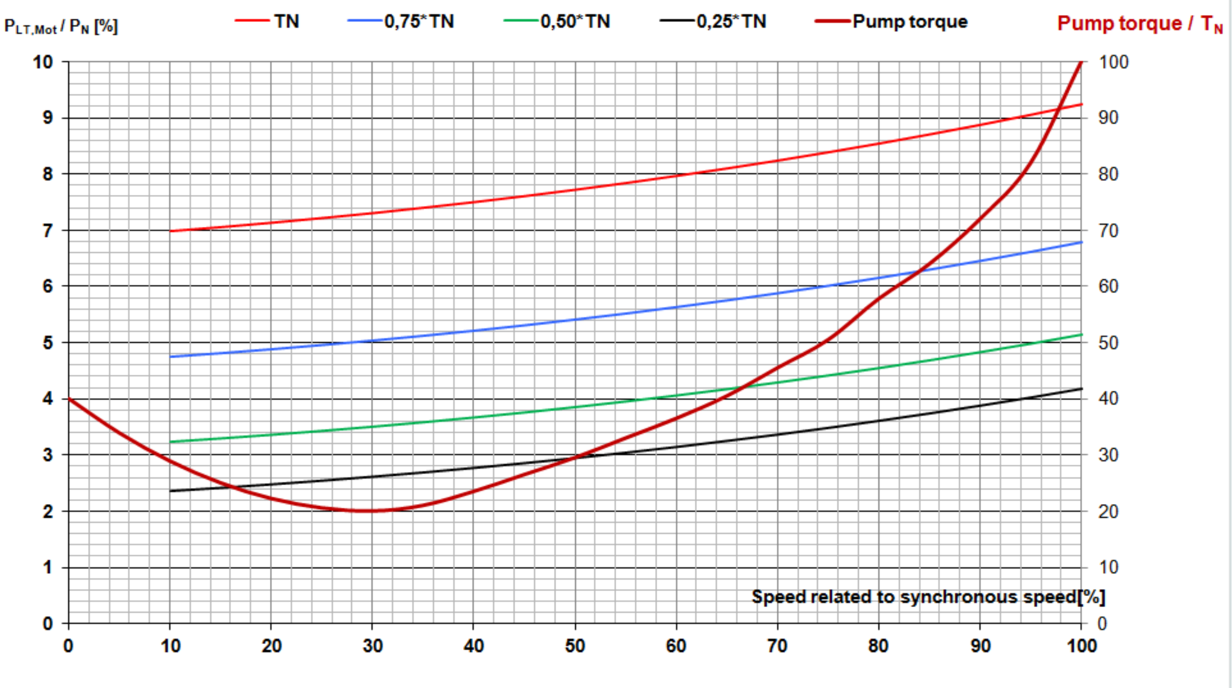


Figure F.3 — Determination of total losses at a running point

Figure F.3 shows how total losses at a certain running point can be determined:

The load is defined by its curve torque versus speed (in the example a pump or a fan)

At 80 % speed, the torque of that load is 58 % T_N

Total losses of motor driven by the converter for that running point will be:

$$P_{LT,Mot}(f, load) = \; 4.5\% + \left[\frac{58-50}{75-50}\right] \cdot [6.15\% - 4.5\%] \tag{F.3}$$

$$P_{LT,Mot}(f, load) \; at \; 80\% \; n_S, T = 58\% \; T_N \; \approx \; 5.03 \; \% \; \; P_{n,Mot} \tag{F.4}$$

$$P_{LT,Mot}(f, load) \; at \; 80\% \; n_S, T = 58\% \; T_N \; \approx \; 1500 \; W \;\; for \; P_{n,Mot} \; = \; 30 \; kW \tag{F.5}$$

Table F.1 — Coefficients for motors 4 pole (IE2) as a function of relative torque

	$P_{LT}/ P_{r,M} = A*[T/T_N]^2 + B*[T/T_N] + C$ set T/T_N in %				
Rated power kW	**Coeff.**	**25 % N_n**	**50 % N_n**	**75 %N_n**	**100 % N_n**
0,12	**A**	5,808E-03	5,867E-03	5,942E-03	6,033E-03
	B	-3,244E-01	-3,367E-01	-3,367E-01	-3,452E-01
	C	3,650E+01	4,098E+01	4,644E+01	5,296E+01
0,18	**A**	3,190E-03	3,239E-03	3,301E-03	3,378E-03
	B	-1,213E-01	-1,259E-01	-1,319E-01	-1,391E-01
	C	2,781E+01	3,143E+01	3,586E+01	4,113E+01
0,25	**A**	2,509E-03	2,572E-03	2,653E-03	2,752E-03
	B	-9,956E-02	-1,039E-01	-1,094E-01	-1,162E-01
	C	2,203E+01	2,536E+01	2,946E+01	3,441E+01
0,37	**A**	2,036E-03	2,072E-03	2,117E-03	2,173E-03
	B	-4,024E-02	-4,224E-02	-4,481E-02	-4,795E-02
	C	1,548E+01	1,787E+01	2,080E+01	2,431E+01
0,55	**A**	1,596E-03	1,610E-03	1,628E-03	1,651E-03
	B	-2,421E-02	-2,582E-02	-2,790E-02	-3,044E-02
	C	1,248E+01	1,430E+01	1,651E+01	1,917E+01
0,75	**A**	1,526E-03	1,543E-03	1,564E-03	1,589E-03
	B	-2,060E-02	-2,166E-02	-2,302E-02	-2,469E-02
	C	9,783E+00	1,135E+01	1,325E+01	1,552E+01
1,1	**A**	1,418E-03	1,433E-03	1,453E-03	1,476E-03
	B	-1,711E-02	-1,834E-02	-1,992E-02	-2,185E-02
	C	8,072E+00	9,564E+00	1,140E+01	1,361E+01
1,5	**A**	1,380E-03	1,397E-03	1,419E-03	1,445E-03
	B	-1,807E-02	-1,933E-02	-2,097E-02	-2,296E-02
	C	6,954E+00	8,267E+00	9,863E+00	1,176E+01
2,2	**A**	1,158E-03	1,173E-03	1,191E-03	1,215E-03
	B	-1,290E-02	-9,983E-03	-6,227E-03	-1,636E-03
	C	5,506E+00	6,622E+00	7,977E+00	9,594E+00
3,0	**A**	1,132E-03	1,159E-03	1,193E-03	1,235E-03

	$P_{LT}/ P_{r,M} = A*[T/T_N]^2 + B*[T/T_N] + C$ set T/T_N in %				
Rated power kW	**Coeff.**	**25 % N_n**	**50 % N_n**	**75 %N_n**	**100 % N_n**
	B	-9,770E-03	-1,056E-02	-1,157E-02	-1,281E-02
	C	4,677E+00	5,649E+00	6,824E+00	8,216E+00
4,0	**A**	9,758E-04	1,005E-03	1,024E-03	1,088E-03
	B	-1,065E-02	-1,179E-02	-1,324E-02	-1,502E-02
	C	4,244E+00	5,315E+00	6,630E+00	8,211E+00
5,5	**A**	8,743E-04	9,152E-04	9,677E-04	1,032E-03
	B	-9,649E-03	-1,060E-02	-1,183E-02	-1,333E-02
	C	3,658E+00	4,633E+00	5,838E+00	7,303E+00
7,5	**A**	9,435E-04	9,817E-04	1,031E-03	1,091E-03
	B	-1,669E-02	-1,757E-02	-1,870E-02	-2,007E-02
	C	3,040E+00	3,897E+00	4,946E+00	6,210E+00
11	**A**	7,561E-04	7,858E-04	8,239E-04	8,705E-04
	B	-1,018E-02	-1,064E-02	-1,124E-02	-1,197E-02
	C	2,627E+00	3,422E+00	4,402E+00	5,588E+00
15	**A**	6,769E-04	7,070E-04	7,456E-04	7,928E-04
	B	-8,912E-03	-9,208E-03	-9,588E-03	-1,005E-02
	C	2,232E+00	2,960E+00	3,860E+00	4,952E+00
18,5	**A**	6,567E-04	6,837E-04	7,184E-04	7,609E-04
	B	-6,265E-03	-6,530E-03	-6,871E-03	-7,288E-03
	C	2,020E+00	2,683E+00	3,500E+00	4,490E+00
22	**A**	6,105E-04	6,258E-04	6,453E-04	6,693E-04
	B	-5,417E-03	-5,810E-03	-6,316E-03	-6,934E-03
	C	1,945E+00	2,604E+00	3,420E+00	4,412E+00
30	**A**	4,821E-04	5,183E-04	5,277E-04	5,511E-04
	B	2,327E-03	-1,000E-03	-2,703E-04	-9,906E-04
	C	2,033E+00	2,521E+00	3,024E+00	3,722E+00
37	**A**	4,214E-04	4,409E-04	4,659E-04	4,965E-04
	B	4,671E-03	4,477E-03	4,227E-03	3,923E-03
	C	1,275E+00	1,856E+00	2,594E+00	3,524E+00

	$P_{LT}/P_{r,M} = A*[T/T_N]^2 + B*[T/T_N] + C$ set T/T_N in %				
Rated power kW	**Coeff.**	**25 % N_n**	**50 % N_n**	**75 %N_n**	**100 % N_n**
45	**A**	4,702E-04	4,920E-04	5,200E-04	5,543E-04
	B	-3,093E-03	-3,227E-03	-3,398E-03	-3,607E-03
	C	1,458E+00	2,010E+00	2,706E+00	3,576E+00
55	**A**	3,863E-04	4,104E-04	4,415E-04	4,795E-04
	B	-3,951E-03	-4,209E-03	-4,541E-03	-4,947E-03
	C	1,379E+00	1,951E+00	2,677E+00	3,585E+00
75	**A**	3,030E-04	3,355E-04	3,772E-04	4,283E-04
	B	-1,657E-03	-1,603E-03	-1,534E-03	-1,449E-03
	C	1,109E+00	1,660E+00	2,361E+00	3,246E+00
90	**A**	2,986E-04	3,261E-04	3,614E-04	4,046E-04
	B	-2,591E-03	-2,556E-03	-2,511E-03	-2,455E-03
	C	1,149E+00	1,685E+00	2,359E+00	3,192E+00
110	**A**	2,598E-04	2,881E-04	3,244E-04	3,689E-04
	B	-2,655E-03	-2,783E-03	-2,947E-03	-3,147E-03
	C	1,483E+00	2,118E+00	2,908E+00	3,883E+00
132	**A**	3,168E-04	3,524E-04	3,982E-04	4,541E-04
	B	-4,441E-03	-4,962E-03	-5,632E-03	-6,451E-03
	C	1,286E+00	1,773E+00	2,368E+00	3,093E+00
160	**A**	2,737E-04	3,106E-04	3,580E-04	4,106E-04
	B	-3,341E-03	-3,819E-03	-4,433E-03	-5,184E-03
	C	1,251E+00	1,746E+00	2,346E+00	3,064E+00
200	**A**	2,666E-04	2,995E-04	3,417E-04	3,933E-04
	B	-3,312E-03	-3,810E-03	-4,450E-03	-5,232E-03
	C	1,196E+00	1,689E+00	2,297E+00	3,043E+00
250	**A**	2,434E-04	2,751E-04	3,158E-04	3,656E-04
	B	-2,568E-03	-3,195E-03	-4,001E-03	-4,986E-03
	C	1,141E+00	1,605E+00	2,180E+00	2,887E+00
315	**A**	2,202E-04	2,507E-04	2,899E-04	3,378E-04

	$P_{LT}/ P_{r,M} = A*[T/T_N]^2 + B*[T/T_N] + C$ set T/T_N in %				
Rated power kW	**Coeff.**	**25 % N_n**	**50 % N_n**	**75 %N_n**	**100 % N_n**
	B	-1,823E-03	-2,579E-03	-3,551E-03	-4,739E-03
	C	1,085E+00	1,522E+00	2,063E+00	2,730E+00
355	**A**	2,138E-04	2,418E-04	2,777E-04	3,216E-04
	B	-1,846E-03	-2,363E-03	-3,026E-03	-3,838E-03
	C	1,036E+00	1,453E+00	1,971E+00	2,612E+00
400	**A**	2,075E-04	2,328E-04	2,655E-04	3,054E-04
	B	-1,870E-03	-2,146E-03	-2,502E-03	-2,937E-03
	C	9,871E-01	1,385E+00	1,879E+00	2,493E+00
500	**A**	2,011E-04	2,239E-04	2,533E-04	2,892E-04
	B	-1,893E-03	-1,930E-03	-1,977E-03	-2,036E-03
	C	9,381E-01	1,316E+00	1,787E+00	2,375E+00
560	**A**	1,733E-04	1,961E-04	2,254E-04	2,611E-04
	B	-1,395E-03	-1,427E-03	-1,468E-03	-1,518E-03
	C	9,124E-01	1,299E+00	1,787E+00	2,404E+00
630	**A**	1,455E-04	1,682E-04	1,974E-04	2,330E-04
	B	-8,974E-04	-9,240E-04	-9,582E-04	-1,000E-03
	C	8,867E-01	1,282E+00	1,787E+00	2,433E+00
710	**A**	1,419E-04	1,646E-04	1,938E-04	2,294E-04
	B	-9,159E-04	-9,421E-04	-9,757E-04	-1,017E-03
	C	8,965E-01	1,304E+00	1,828E+00	2,505E+00
800	**A**	1,382E-04	1,609E-04	1,901E-04	2,257E-04
	B	-9,344E-04	-9,601E-04	-9,931E-04	-1,033E-03
	C	9,063E-01	1,326E+00	1,869E+00	2,576E+00
900	**A**	1,365E-04	1,592E-04	1,883E-04	2,239E-04
	B	-9,682E-04	-9,941E-04	-1,027E-03	-1,067E-03
	C	8,515E-01	1,241E+00	1,741E+00	2,388E+00
1 000	**A**	1,347E-04	1,574E-04	1,864E-04	2,220E-04
	B	-1,002E-03	-1,028E-03	-1,061E-03	-1,101E-03
	C	7,967E-01	1,155E+00	1,613E+00	2,200E+00

Table F.2 — Coefficients for motors 4 pole (IE2) as a function of relative speed

	$P_{LT}/ P_{r,M}$ = $A*[n/n_N]^2 + B*[n/n_N] + C$ set n/n_N in %				
Rated power kW	**Coeff.**	**25 % T_n**	**50 % T_n**	**75 % T_n**	**100 % T_n**
0,12	**A**	7,750E-04	7,708E-04	7,792E-04	8,083E-04
	B	1,172E-01	1,168E-01	1,176E-01	1,205E-01
	C	2,832E+01	3,223E+01	4,057E+01	5,890E+01
0,18	**A**	6,278E-04	6,222E-04	6,306E-04	6,528E-04
	B	9,471E-02	9,415E-02	9,498E-02	9,721E-02
	C	2,392E+01	2,720E+01	3,365E+01	4,481E+01
0,25	**A**	6,155E-04	6,195E-04	6,375E-04	6,775E-04
	B	8,444E-02	8,484E-02	8,664E-02	9,064E-02
	C	1,855E+01	2,095E+01	2,595E+01	3,451E+01
0,37	**A**	4,267E-04	4,307E-04	4,443E-04	4,686E-04
	B	6,284E-02	6,324E-02	6,459E-02	6,703E-02
	C	1,390E+01	1,671E+01	2,200E+01	2,984E+01
0,55	**A**	3,208E-04	3,172E-04	3,190E-04	3,235E-04
	B	4,742E-02	4,705E-02	4,724E-02	4,769E-02
	C	1,148E+01	1,389E+01	1,824E+01	2,462E+01
0,75	**A**	2,700E-04	2,706E-04	2,766E-04	2,866E-04
	B	4,180E-02	4,186E-02	4,246E-02	4,346E-02
	C	8,994E+00	1,138E+01	1,555E+01	2,173E+01
1,1	**A**	2,750E-04	2,746E-04	2,782E-04	2,864E-04
	B	3,832E-02	3,828E-02	3,864E-02	3,946E-02
	C	7,377E+00	9,677E+00	1,357E+01	1,939E+01
1,5	**A**	2,253E-04	2,250E-04	2,303E-04	2,396E-04
	B	3,486E-02	3,483E-02	3,536E-02	3,629E-02
	C	6,342E+00	8,508E+00	1,231E+01	1,790E+01
2,2	**A**	2,106E-04	2,459E-04	2,547E-04	2,984E-04
	B	3,166E-02	3,518E-02	3,607E-02	4,043E-02
	C	4,692E+00	6,776E+00	9,930E+00	1,461E+01
3,0	**A**	1,634E-04	1,702E-04	1,847E-04	2,067E-04
	B	2,657E-02	2,725E-02	2,870E-02	3,090E-02

	$P_{LT}/ P_{r,M} = A*[n/n_N]^2 + B*[n/n_N] + C$ set n/n_N in %				
Rated power kW	**Coeff.**	**25 % T_n**	**50 % T_n**	**75 % T_n**	**100 % T_n**
	C	4,363E+00	6,253E+00	9,453E+00	1,413E+01
4,0	**A**	1,965E-04	2,021E-04	2,170E-04	2,393E-04
	B	2,778E-02	2,834E-02	2,983E-02	3,205E-02
	C	3,771E+00	5,301E+00	8,061E+00	1,198E+01
5,5	**A**	1,889E-04	2,013E-04	2,245E-04	2,603E-04
	B	2,499E-02	2,623E-02	2,855E-02	3,213E-02
	C	3,209E+00	4,596E+00	6,972E+00	1,047E+01
7,5	**A**	1,581E-04	1,698E-04	1,915E-04	2,250E-04
	B	2,253E-02	2,370E-02	2,587E-02	2,922E-02
	C	2,540E+00	3,886E+00	6,302E+00	9,940E+00
11	**A**	1,530E-04	1,632E-04	1,815E-04	2,087E-04
	B	2,064E-02	2,176E-02	2,349E-02	2,621E-02
	C	2,224E+00	3,381E+00	5,394E+00	8,388E+00
15	**A**	1,435E-04	1,547E-04	1,745E-04	2,028E-04
	B	1,887E-02	1,998E-02	2,196E-02	2,480E-02
	C	1,861E+00	2,902E+00	4,688E+00	7,368E+00
18,5	**A**	1,283E-04	1,384E-04	1,561E-04	1,816E-04
	B	1,737E-02	1,838E-02	2,015E-02	2,271E-02
	C	1,751E+00	2,818E+00	4,622E+00	7,283E+00
22	**A**	1,286E-04	1,329E-04	1,415E-04	1,545E-04
	B	1,675E-02	1,718E-02	1,804E-02	1,934E-02
	C	1,688E+00	2,689E+00	4,427E+00	6,927E+00
30	**A**	8,753E-05	1,124E-04	1,554E-04	1,668E-04
	B	1,455E-02	1,563E-02	1,757E-02	1,968E-02
	C	1,351E+00	2,233E+00	3,734E+00	5,949E+00
37	**A**	1,544E-04	1,187E-04	1,268E-04	1,402E-04
	B	2,324E-03	7,806E-03	8,616E-03	9,547E-03
	C	2,336E+00	3,080E+00	4,566E+00	6,795E+00
45	**A**	1,224E-04	1,309E-04	1,458E-04	1,668E-04

	$P_{\mathrm{LT}}/ P_{\mathrm{r,M}} = A*[n/n_{\mathrm{N}}]^2 + B*[n/n_{\mathrm{N}}] + C$ set n/n_{N} in %				
Rated power kW	**Coeff.**	**25 % T_n**	**50 % T_n**	**75 % T_n**	**100 % T_n**
	B	1,340E-02	1,426E-02	1,574E-02	1,785E-02
	C	1,257E+00	2,040E+00	3,378E+00	5,297E+00
55	**A**	1,294E-04	1,381E-04	1,541E-04	1,767E-04
	B	1,362E-02	1,449E-02	1,609E-02	1,835E-02
	C	1,029E+00	1,706E+00	2,741E+00	4,277E+00
75	**A**	1,311E-04	1,454E-04	1,688E-04	2,017E-04
	B	1,313E-02	1,455E-02	1,690E-02	2,018E-02
	C	8,411E-01	1,330E+00	E+00	3,340E+00
90	**A**	1,185E-04	1,304E-04	1,503E-04	1,779E-04
	B	1,330E-02	1,450E-02	1,648E-02	1,925E-02
	C	8,599E-01	1,325E+00	2,121E+00	3,283E+00
110	**A**	1,322E-04	1,436E-04	1,630E-04	1,906E-04
	B	1,615E-02	1,729E-02	1,924E-02	2,199E-02
	C	1,086E+00	1,480E+00	2,151E+00	3,144E+00
132	**A**	9,239E-05	1,049E-04	1,270E-04	1,599E-04
	B	1,295E-02	1,420E-02	1,641E-02	1,970E-02
	C	9,861E-01	1,441E+00	2,234E+00	3,417E+00
160	**A**	8,888E-05	1,022E-04	1,255E-04	1,599E-04
	B	1,359E-02	1,493E-02	1,725E-02	2,069E-02
	C	9,389E-01	1,336E+00	2,021E+00	3,037E+00
200	**A**	9,772E-05	1,093E-04	1,294E-04	1,598E-04
	B	1,275E-02	1,391E-02	1,592E-02	1,895E-02
	C	8,943E-01	1,285E+00	1,958E+00	2,957E+00
250	**A**	9,238E-05	1,030E-04	1,211E-04	1,498E-04
	B	1,185E-02	1,292E-02	1,473E-02	1,759E-02
	C	8,695E-01	1,237E+00	1,865E+00	2,784E+00
315	**A**	8,703E-05	9,665E-05	1,128E-04	1,398E-04
	B	1,095E-02	1,192E-02	1,353E-02	1,623E-02
	C	8,447E-01	1,188E+00	1,771E+00	2,611E+00

	$P_{LT}/ P_{r,M} = A*[n/n_N]^2 + B*[n/n_N] + C$ set n/n_N in %				
Rated power kW	**Coeff.**	**25 % T_n**	**50 % T_n**	**75 % T_n**	**100 % T_n**
355	**A**	8,509E-05	9,470E-05	1,108E-04	1,364E-04
	B	1,051E-02	1,148E-02	1,309E-02	1,564E-02
	C	8,032E-01	1,134E+00	1,697E+00	2,513E+00
400	**A**	8,316E-05	9,276E-05	1,089E-04	1,329E-04
	B	1,007E-02	1,103E-02	1,264E-02	1,505E-02
	C	7,617E-01	1,080E+00	1,274E+00	2,414E+00
500	**A**	8,122E-05	9,081E-05	1,069E-04	1,295E-04
	B	9,629E-03	1,059E-02	1,220E-02	1,446E-02
	C	7,202E-01	1,026E+00	1,548E+00	2,316E+00
560	**A**	8,849E-05	9,806E-05	6,605E-05	1,367E-04
	B	9,450E-03	1,041E-02	1,202E-02	1,427E-02
	C	6,893E-01	9,536E-01	1,143E+00	2,061E+00
630	**A**	9,575E-05	1,053E-04	1,214E-04	1,439E-04
	B	9,270E-03	1,023E-02	1,183E-02	1,408E-02
	C	6,584E-01	8,812E-01	1,260E+00	1,806E+00
710	**A**	1,020E-04	1,116E-04	1,277E-04	1,502E-04
	B	9,300E-03	1,026E-02	1,186E-02	1,412E-02
	C	6,601E-01	8,760E-01	1,242E+00	1,772E+00
800	**A**	1,082E-04	1,178E-04	1,339E-04	1,564E-04
	B	9,330E-03	1,029E-02	1,189E-02	1,415E-02
	C	6,618E-01	8,708E-01	1,224E+00	1,738E+00
900	**A**	9,776E-05	1,073E-04	1,234E-04	1,459E-04
	B	8,874E-03	9,832E-03	1,143E-02	1,369E-02
	C	6,238E-01	8,288E-01	1,176E+00	1,682E+00
	A	8,731E-05	9,687E-05	1,129E-04	1,353E-04
1 000	**B**	8,417E-03	9,373E-03	1,097E-02	1,322E-02
	C	5,857E-01	7,867E-01	1,128E+00	1,625E+00

Table F.3 — Coefficients for motors 2 pole (IE2) as a function of relative torque

	$P_{LT}/ P_{r.M} = A*[T/T_N]^2 + B*[T/T_N] + C$ set T/T_N in %				
Rated power kW	**Coeff.**	**25 % N_n**	**50 % N_n**	**75 % N_n**	**100 % N_n**
0,12	**A**	7,473E-03	7,575E-03	7,706E-03	7,867E-03
	B	-4,122E-01	-4,240E-01	-4,393E-01	-4,580E-01
	C	3,507E+01	4,020E+01	4,675E+01	5,500E+01
0,18	**A**	5,630E-03	5,703E-03	5,797E-03	5,911E-03
	B	-3,495E-01	-3,564E-01	-3,653E-01	-3,762E-01
	C	3,026E+01	3,466E+01	4,048E+01	4,808E+01
0,25	**A**	4,537E-03	4,618E-03	4,721E-03	4,848E-03
	B	-2,023E-01	-2,090E-01	-2,177E-01	-2,282E-01
	C	1,946E+01	2,310E+01	2,784E+01	3,396E+01
0,37	**A**	3,203E-03	3,297E-03	3,419E-03	3,568E-03
	B	-1,281E-01	-1,338E-01	-1,412E-01	-1,502E-01
	C	1,307E+01	1,594E+01	1,973E+01	2,467E+01
0,55	**A**	2,706E-03	2,798E-03	2,917E-03	3,062E-03
	B	-1,002E-01	-1,049E-01	-1,110E-01	-1,185E-01
	C	9,744E+00	1,223E+01	1,551E+01	1,977E+01
0,75	**A**	2,589E-03	2,637E-03	2,698E-03	2,773E-03
	B	-6,924E-02	-7,100E-02	-7,328E-02	-7,605E-02
	C	8,613E+00	1,022E+01	1,227E+01	1,488E+01
1,1	**A**	1,849E-03	1,887E-03	1,936E-03	1,996E-03
	B	-3,928E-02	-4,075E-02	-4,263E-02	-4,493E-02
	C	6,711E+00	8,114E+00	9,904E+00	1,217E+01
1,5	**A**	1,360E-03	1,379E-03	1,403E-03	1,432E-03
	B	-2,153E-02	-2,309E-02	-2,510E-02	-2,756E-02
	C	7,035E+00	8,596E+00	1,065E+01	1,333E+01
2,2	**A**	1,357E-03	1,384E-03	1,418E-03	1,460E-03
	B	-2,587E-02	-2,777E-02	-3,022E-02	-3,321E-02
	C	6,859E+00	8,300E+00	1,016E+01	1,251E+01
3,0	**A**	1,123E-03	1,156E-03	1,199E-03	1,252E-03
	B	-1,045E-02	-1,134E-02	-1,248E-02	-1,387E-02

	$P_{LT}/ P_{r.M}$ = A*[T/T_N]² + B*[T/T_N] + C set T/T_N in %				
Rated power kW	**Coeff.**	**25 % N_n**	**50 % N_n**	**75 %N_n**	**100 % N_n**
	C	5,152E+00	6,349E+00	7,890E+00	9,851E+00
4,0	**A**	1,015E-03	1,078E-03	1,160E-03	1,259E-03
	B	-1,436E-02	-1,507E-02	-1,599E-02	-1,710E-02
	C	3,986E+00	5,087E+00	6,519E+00	8,358E+00
5,5	**A**	9,024E-04	9,205E-04	9,439E-04	9,724E-04
	B	-1,217E-02	-1,278E-02	-1,357E-02	-1,454E-02
	C	3,654E+00	4,749E+00	6,206E+00	8,119E+00
7,5	**A**	8,964E-04	9,374E-04	9,000E-04	1,054E-03
	B	-1,668E-02	-1,699E-02	-1,739E-02	-1,787E-02
	C	2,993E+00	3,750E+00	4,743E+00	6,040E+00
11	**A**	6,894E-04	7,190E-04	7,569E-04	8,033E-04
	B	-6,503E-03	-6,764E-03	-7,100E-03	-7,511E-03
	C	2,064E+00	2,676E+00	3,467E+00	4,482E+00
15	**A**	6,099E-04	6,384E-04	6,750E-04	7,197E-04
	B	-4,400E-03	-4,801E-03	-5,317E-03	-5,948E-03
	C	2,138E+00	2,960E+00	4,085E+00	5,610E+00
18,5	**A**	5,406E-04	5,651E-04	5,967E-04	6,352E-04
	B	-5,943E-03	-6,160E-03	-6,440E-03	-6,783E-03
	C	1,947E+00	2,696E+00	3,731E+00	5,145E+00
22	**A**	5,024E-04	5,306E-04	5,669E-04	6,113E-04
	B	-4,580E-03	-4,740E-03	-4,946E-03	-5,198E-03
	C	1,530E+00	2,168E+00	3,033E+00	4,192E+00
30	**A**	4,351E-04	4,672E-04	5,085E-04	5,589E-04
	B	-2,317E-03	-2,557E-03	-2,867E-03	-3,245E-03
	C	1,535E+00	2,250E+00	3,248E+00	4,612E+00
37	**A**	4,791E-04	5,113E-04	5,527E-04	6,023E-04
	B	-7,630E-03	-7,910E-03	-8,269E-03	-8,709E-03
	C	1,378E+00	1,998E+00	2,866E+00	4,065E+00
45	**A**	3,211E-04	3,425E-04	3,700E-04	4,036E-04

	$P_{LT}/P_{r.M} = A*[T/T_N]^2 + B*[T/T_N] + C$ set T/T_N in %				
Rated power kW	**Coeff.**	**25 % N_n**	**50 % N_n**	**75 %N_n**	**100 % N_n**
	B	-2,500E-03	-2,830E-03	-3,254E-03	-3,772E-03
	C	1,198E+00	1,843E+00	2,720E+00	3,889E+00
55	**A**	3,302E-04	3,519E-04	3,798E-04	4,138E-04
	B	-1,770E-03	-1,791E-03	-1,817E-03	-1,849E-03
	C	1,220E+00	1,860E+00	2,757E+00	3,993E+00
75	**A**	2,606E-04	2,744E-04	2,921E-04	3,138E-04
	B	-1,117E-03	-1,507E-03	-2,008E-03	-2,620E-03
	C	1,225E+00	1,955E+00	2,995E+00	4,444E+00
90	**A**	2,551E-04	2,761E-04	3,030E-04	3,360E-04
	B	-6,663E-04	-7,724E-04	-9,089E-04	-1,076E-03
	C	1,490E+00	2,176E+00	3,101E+00	4,337E+00
110	**A**	2,107E-04	2,285E-04	2,514E-04	2,793E-04
	B	-1,532E-03	-1,531E-03	-1,531E-03	-1,530E-03
	C	1,238E+00	1,849E+00	2,688E+00	3,829E+00
132	**A**	2,099E-04	2,304E-04	2,568E-04	2,890E-04
	B	-1,374E-03	-1,408E-03	-1,453E-03	-1,507E-03
	C	1,147E+00	1,701E+00	2,463E+00	3,507E+00
160	**A**	2,090E-04	2,322E-04	2,621E-04	2,986E-04
	B	-1,216E-03	-1,285E-03	-1,374E-03	-1,483E-03
	C	1,057E+00	1,553E+00	2,239E+00	3,185E+00
200	**A**	2,134E-04	2,496E-04	2,962E-04	3,531E-04
	B	-2,597E-03	-3,751E-03	-5,236E-03	-7,050E-03
	C	1,017E+00	1,486E+00	2,118E+00	2,965E+00
250	**A**	1,850E-04	2,079E-04	2,373E-04	2,735E-04
	B	-1,219E-03	-1,322E-03	-1,362E-03	-1,411E-03
	C	1,031E+00	1,507E+00	2,166E+00	3,074E+00
315	**A**	1,819E-04	2,048E-04	2,342E-04	2,701E-04
	B	-1,355E-03	-1,391E-03	-1,439E-03	-1,497E-03
	C	9,168E-01	1,329E+00	1,892E+00	2,657E+00

	$P_{LT}/ P_{r.M} = A*[T/T_N]^2 + B*[T/T_N] + C$ set T/T_N in %				
Rated power kW	**Coeff.**	**25 % N_n**	**50 % N_n**	**75 % N_n**	**100 % N_n**
355	**A**	1,718E-04	1,947E-04	2,240E-04	2,598E-04
	B	-1,313E-03	-1,346E-03	-1,390E-03	-1,443E-03
	C	8,729E-01	1,266E+00	1,802E+00	2,532E+00
400	**A**	1,618E-04	1,845E-04	2,137E-04	2,494E-04
	B	-1,270E-03	-1,301E-03	-1,340E-03	-1,388E-03
	C	8,289E-01	1,202E+00	1,712E+00	2,407E+00
500	**A**	1,517E-04	1,744E-04	2,035E-04	2,391E-04
	B	-1,228E-03	-1,256E-03	-1,291E-03	-1,334E-03
	C	7,850E-01	1,139E+00	1,622E+00	2,282E+00
560	**A**	1,400E-04	1,627E-04	1,918E-04	2,273E-04
	B	-9,567E-04	-9,800E-04	-1,016E-03	-1,056E-03
	C	7,635E-01	1,115E+00	1,597E+00	2,255E+00
630	**A**	1,283E-04	1,509E-04	1,800E-04	2,155E-04
	B	-6,854E-04	-7,039E-04	-7,401E-04	-7,778E-04
	C	7,420E-01	1,092E+00	1,572E+00	2,228E+00
710	**A**	1,144E-04	1,369E-04	1,660E-04	2,015E-04
	B	-5,674E-04	-5,868E-04	-6,180E-04	-6,529E-04
	C	7,482E-01	1,117E+00	1,630E+00	2,340E+00
800	**A**	1,004E-04	1,229E-04	1,519E-04	1,874E-04
	B	-4,493E-04	-4,697E-04	-4,959E-04	-5,280E-04
	C	7,544E-01	1,143E+00	1,689E+00	2,451E+00
900	**A**	1,107E-04	1,332E-04	1,622E-04	1,977E-04
	B	-6,901E-04	-7,118E-04	-7,398E-04	-7,740E-04
	C	7,221E-01	1,079E+00	1,576E+00	2,267E+00
1 000	**A**	1,209E-04	1,435E-04	1,724E-04	2,079E-04
	B	-9,309E-04	-9,539E-04	-9,836E-04	-1,020E-03
	C	6,898E-01	1,014E+00	1,463E+00	2,084E+00

Table F.4 — Coefficients for motors 2 pole (IE2) as a function of relative speed

	$P_{LT}/P_{r,M} = A*[n/n_N]^2 + B*[n/n_N] + C$ set n/n_N in %				
Rated power kW	**Coeff.**	**25 % T_n**	**50 % T_n**	**75 % T_n**	**100 % T_n**
0,12	**A**	1,127E-03	1,106E-03	1,106E-03	1,144E-03
	B	1,120E-01	1,100E-01	1,100E-01	1,137E-01
	C	2,560E+01	3,052E+01	4,185E+01	6,527E+01
0,18	**A**	1,167E-03	1,156E-03	1,172E-03	1,203E-03
	B	8,452E-02	8,341E-02	8,508E-02	8,813E-02
	C	2,207E+01	2,423E+01	3,257E+01	4,868E+01
0,25	**A**	9,040E-04	9,020E-04	9,180E-04	9,620E-04
	B	7,353E-02	7,333E-02	7,493E-02	7,933E-02
	C	1,468E+01	1,864E+01	2,696E+01	4,212E+01
0,37	**A**	7,518E-04	7,612E-04	7,936E-04	8,572E-04
	B	5,574E-02	5,668E-02	5,993E-02	6,628E-02
	C	9,891E+00	1,297E+01	1,922E+01	3,013E+01
0,55	**A**	6,460E-04	6,605E-04	6,960E-04	7,633E-04
	B	4,917E-02	5,063E-02	5,417E-02	6,090E-02
	C	7,198E+00	1,002E+01	1,542E+01	2,483E+01
0,75	**A**	3,729E-04	3,829E-04	4,075E-04	4,449E-04
	B	3,595E-02	3,695E-02	3,941E-02	4,315E-02
	C	7,305E+00	1,058E+01	1,658E+01	2,625E+01
1,1	**A**	3,213E-04	3,286E-04	3,486E-04	3,777E-04
	B	3,177E-02	3,249E-02	3,449E-02	3,740E-02
	C	5,861E+00	8,389E+00	1,303E+01	2,011E+01
1,5	**A**	4,110E-04	4,097E-04	4,147E-04	4,240E-04
	B	3,091E-02	3,078E-02	3,128E-02	3,221E-02
	C	6,293E+00	8,333E+00	1,199E+01	1,740E+01
2,2	**A**	3,382E-04	3,384E-04	3,417E-04	3,625E-04
	B	3,131E-02	3,134E-02	3,220E-02	3,375E-02
	C	6,049E+00	7,967E+00	1,150E+01	1,677E+01
3,0	**A**	2,874E-04	2,971E-04	3,154E-04	3,442E-04
	B	2,646E-02	2,743E-02	2,926E-02	3,215E-02

	$P_{\text{LT}}/ P_{\text{r,M}} = A*[n/n_{\text{N}}]^2 + B*[n/n_{\text{N}}] + C$ set n/n_{N} in %				
Rated power kW	**Coeff.**	**25 % T_n**	**50 % T_n**	**75 % T_n**	**100 % T_n**
	C	4,742E+00	6,549E+00	9,749E+00	1,430E+01
4,0	**A**	2,812E-04	3,050E-04	3,450E-04	4,049E-04
	B	2,403E-02	2,641E-02	3,041E-02	3,639E-02
	C	3,460E+00	4,983E+00	7,593E+00	1,154E+01
5,5	**A**	3,034E-04	3,076E-04	3,172E-04	3,317E-04
	B	2,116E-02	2,158E-02	2,254E-02	2,399E-02
	C	3,171E+00	4,591E+00	7,009E+00	1,065E+01
7,5	**A**	2,043E-04	2,200E-04	2,475E-04	2,867E-04
	B	1,584E-02	1,742E-02	2,017E-02	2,408E-02
	C	2,594E+00	3,846E+00	6,089E+00	9,509E+00
11	**A**	1,532E-04	1,642E-04	1,840E-04	2,119E-04
	B	1,360E-02	1,470E-02	1,668E-02	1,947E-02
	C	1,893E+00	2,977E+00	4,925E+00	7,680E+00
15	**A**	2,605E-04	2,703E-04	2,885E-04	3,146E-04
	B	1,390E-02	1,488E-02	1,670E-02	1,931E-02
	C	1,886E+00	2,888E+00	4,628E+00	7,104E+00
18,5	**A**	2,460E-04	2,553E-04	2,715E-04	2,949E-04
	B	1,216E-02	1,309E-02	1,472E-02	1,705E-02
	C	1,662E+00	2,513E+00	3,980E+00	6,139E+00
22	**A**	1,955E-04	2,066E-04	2,260E-04	2,532E-04
	B	1,159E-02	1,270E-02	1,464E-02	1,737E-02
	C	1,305E+00	2,109E+00	3,487E+00	5,497E+00
30	**A**	2,440E-04	2,565E-04	2,779E-04	3,088E-04
	B	1,113E-02	1,238E-02	1,452E-02	1,761E-02
	C	1,301E+00	2,037E+00	3,246E+00	5,012E+00
37	**A**	2,146E-04	2,264E-04	2,483E-04	2,786E-04
	B	9,500E-03	1,068E-02	1,288E-02	1,590E-02
	C	1,097E+00	1,792E+00	2,993E+00	4,828E+00
45	**A**	1,962E-04	2,043E-04	2,169E-04	2,364E-04

	$P_{LT}/ P_{r,M} = A*[n/n_N]^2 + B*[n/n_N] + C$ set n/n_N in %				
Rated power kW	**Coeff.**	**25 % T_n**	**50 % T_n**	**75 % T_n**	**100 % T_n**
	B	1,147E-02	1,219E-02	1,335E-02	1,549E-02
	C	9,187E-01	1,435E+00	2,335E+00	3,615E+00
55	**A**	2,221E-04	2,311E-04	2,467E-04	2,681E-04
	B	9,687E-03	1,095E-02	1,215E-02	1,429E-02
	C	9,891E-01	1,539E+00	2,473E+00	3,810E+00
75	**A**	2,638E-04	2,673E-04	2,752E-04	2,866E-04
	B	9,647E-03	9,999E-03	1,078E-02	1,192E-02
	C	9,398E-01	1,390E+00	2,151E+00	3,229E+00
90	**A**	2,048E-04	2,132E-04	2,276E-04	2,479E-04
	B	1,272E-02	1,356E-02	1,500E-02	1,703E-02
	C	1,177E+00	1,610E+00	2,349E+00	3,383E+00
110	**A**	1,967E-04	2,044E-04	2,170E-04	2,348E-04
	B	1,035E-02	1,111E-02	1,238E-02	1,416E-02
	C	9,370E-01	1,277E+00	1,847E+00	2,682E+00
132	**A**	1,816E-04	1,903E-04	2,046E-04	2,250E-04
	B	9,196E-03	1,006E-02	1,150E-02	1,353E-02
	C	8,893E-01	1,227E+00	1,795E+00	2,621E+00
160	**A**	1,665E-04	1,762E-04	1,922E-04	2,152E-04
	B	8,041E-03	9,009E-03	1,061E-02	1,290E-02
	C	8,415E-01	1,177E+00	1,743E+00	2,560E+00
200	**A**	1,372E-04	1,456E-04	1,656E-04	1,947E-04
	B	8,391E-03	9,237E-03	1,123E-02	1,415E-02
	C	7,822E-01	1,094E+00	1,629E+00	2,410E+00
250	**A**	1,603E-04	1,700E-04	1,861E-04	2,088E-04
	B	7,738E-03	8,702E-03	1,032E-02	1,259E-02
	C	8,102E-01	1,099E+00	1,588E+00	2,298E+00
315	**A**	1,317E-04	1,413E-04	1,574E-04	1,800E-04
	B	7,297E-03	8,258E-03	9,867E-03	1,213E-02
	C	7,234E-01	1,005E+00	1,483E+00	2,178E+00

	$P_{LT}/P_{r,M} = A*[n/n_N]^2 + B*[n/n_N] + C$ set n/n_N in %				
Rated power kW	**Coeff.**	**25 % T_n**	**50 % T_n**	**75 % T_n**	**100 % T_n**
355	**A**	1,260E-04	1,356E-04	1,516E-04	1,742E-04
	B	6,938E-03	7,898E-03	9,504E-03	1,176E-02
	C	6,871E-01	9,507E-01	1,398E+00	2,051E+00
400	**A**	1,202E-04	1,298E-04	1,459E-04	1,684E-04
	B	6,579E-03	7,537E-03	9,141E-03	1,140E-02
	C	6,508E-01	8,965E-01	1,314E+00	1,924E+00
500	**A**	1,145E-04	1,241E-04	1,401E-04	1,626E-04
	B	6,220E-03	7,177E-03	8,778E-03	1,103E-02
	C	6,145E-01	8,423E-01	1,230E+00	1,796E+00
560	**A**	1,147E-04	1,243E-04	1,403E-04	1,628E-04
	B	6,131E-03	7,087E-03	8,679E-03	1,094E-02
	C	5,949E-01	8,065E-01	1,166E+00	1,687E+00
630	**A**	1,149E-04	1,244E-04	1,404E-04	1,629E-04
	B	6,042E-03	6,997E-03	8,579E-03	1,084E-02
	C	5,753E-01	7,707E-01	1,102E+00	1,578E+00
710	**A**	1,266E-04	1,362E-04	1,522E-04	1,746E-04
	B	5,965E-03	6,920E-03	8,511E-03	1,077E-02
	C	5,696E-01	7,413E-01	1,032E+00	1,450E+00
800	**A**	1,383E-04	1,479E-04	1,639E-04	1,863E-04
	B	5,887E-03	6,843E-03	8,442E-03	1,069E-02
	C	5,638E-01	7,119E-01	9,628E-01	1,322E+00
900	**A**	1,245E-04	1,340E-04	1,500E-04	1,724E-04
	B	5,616E-03	6,572E-03	8,169E-03	1,042E-02
	C	5,479E-01	7,105E-01	9,857E-01	1,385E+00
	A	1,106E-04	1,201E-04	1,361E-04	1,585E-04
1 000	**B**	5,345E-03	6,300E-03	7,895E-03	1,014E-02
	C	5,320E-01	7,090E-01	1,009E+00	1,448E+00

NOTE The factor for the additional losses in the motor due to converter fed operation changes according to 5.2.2.6 from 15 % to 25 % between the output powers of 90 kW and 110 kW. This causes a discontinuity in the tabular values.

The values in Table F.1 to Table F.4 give the coefficients for the parabolic functions according to Formula (F.1) and Formula (F.2) for 2- and 4-pole IE2 motors available on the market.

Annex G
(informative)

Application example for loss calculations of a CDM and a PDS

G.1 General

In this section, an example is given how to calculate the losses of a real CDM and a real PDS at a defined operation point. The operating point of the PDS is chosen to be at 80 % rated torque and 75 % rated speed of a 7,5kW example PDS.

For this purpose, the losses of the CDM are calculated first. In the next step, the motor losses are determined. In the third step, the PDS losses are calculated.

G.2 CDM loss determination

G.2.1 General

In order to determine the relative losses of a CDM at an arbitrary operating point, one of the following calculation models can be used:

a) maximum losses in neighbouring predefined loss points;

b) two-dimensional linear inter- or extrapolation from neighbouring loss points;

c) loss calculation according to the mathematical model described in 5.2.

For the models a) and b), it is necessary to divide the operating area shown in Figure 5 into four segments.

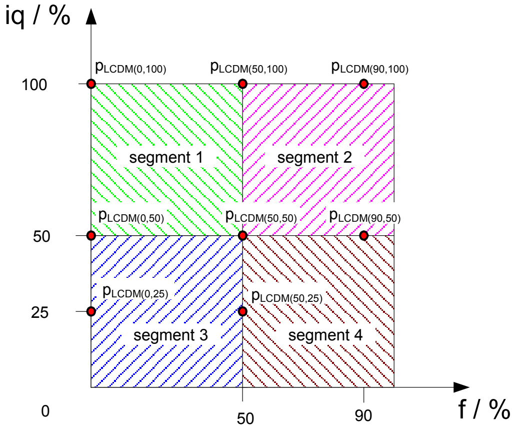


Figure G.1 — Segments of operating points

Segment 1 covers the operating points up to 50 % relative motor stator frequency f and above 50 % relative torque producing current iq.

Segment 2 covers the operating points above 50 % relative motor stator frequency f and above 50 % relative torque producing current iq.

Segment 3 covers the operating points up to 50 % relative motor stator frequency f and up to 50 % relative torque producing current iq.

Segment 4 covers the operating points above 50 % relative motor stator frequency f and up to 50 % relative torque producing current iq.

In the following sub-sections, it is demonstrated how to determine the losses at the operating point of 75 % relative motor stator frequency and 80 % relative torque producing current. The example CDM which is used in the example PDS has a rated apparent power of 9,9kVA. The losses in the predefined operating points are assumed to be as follows:

Table G.1 — Relative losses of a 400V/9,95kVA example CDM at the predefined operating points

P_{r}M / kW	$S_{\mathrm{r,equ}}$ /kVA	$p_{\mathrm{L,CDM}}$ (0;25)	$p_{\mathrm{L,CDM}}$ (0;50)	$p_{\mathrm{L,CDM}}$ (0;100)	$p_{\mathrm{L,CDM}}$ (50;25)	$p_{\mathrm{L,CDM}}$ (50;50)	$p_{\mathrm{L,CDM}}$ (50;100)	$p_{\mathrm{L,CDM,}}$ (90;50)	$p_{\mathrm{L,CDM}}$ (90;100)
7,5	9,95	2,56	2,88	3,89	2,64	3,09	4,58	3,45	5,91

G.2.2 Loss determination by maximum losses of neighbouring loss points

This way to determine the losses is very simple. However, it provides a higher deviation from the correct result than the other methods.

The evaluated operating point at 75 % relative motor stator frequency and 80 % of torque producing current belongs to segment 2 according to Figure G.1. Consequently, the neighbouring operating points are $p_{\mathrm{L,CDM}\ (50;50)}$, $p_{\mathrm{L,CDM}\ (50;100)}$,$p_{\mathrm{L,CDM}\ (90;50)}$ and $p_{\mathrm{L,CDM}\ (90;100)}$. The predefined operating point with maximum losses is $p_{\mathrm{L,CDM}\ (90;100)}$. Consequently, the losses at 75 % relative motor stator frequency and 80 % torque producing current are determined to 5,91 %.

G.2.3 Loss determination by two-dimensional interpolation of losses of neighbouring loss points

G.2.3.1 General two- dimensional interpolation model

Interpolation between four defined points A, B. C and D at an operating point Z is calculated in three steps.

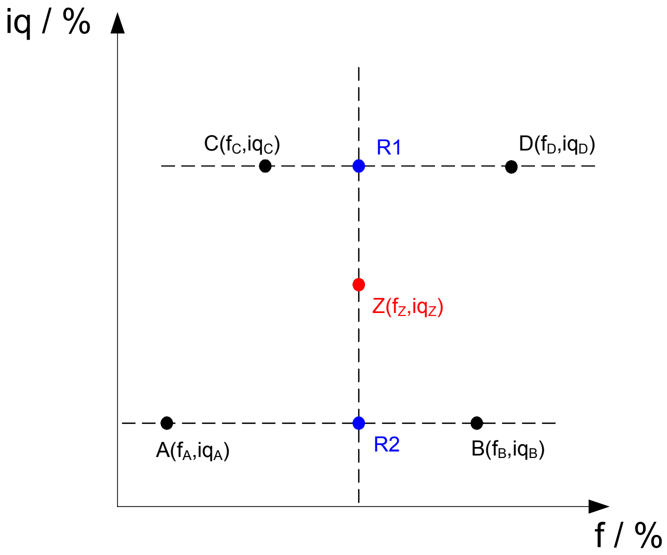


Figure G.2 — Two-dimensional interpolation

In the first step, a linear interpolation between Points C and D is calculated for the point R1. The horizontal component f of $R1$ is chosen equivalent to the horizontal component f_Z of the required operating point Z. If the vertical component of the points C and D are identical ($iq_C=iq_D$), the losses at the point $R1$ are a function of the horizontal component f_Z only and can be calculated by:

$$p_{L,R1}(f_Z) = p_{L,C} + \frac{p_{L,D} - p_{L,C}}{f_D - f_C} \cdot (f_Z - f_C) \tag{G.1}$$

In the second step, the losses are interpolated in the same way for the point $R2$:

$$P_{L,R2}(f_z) = P_{L,A} + \frac{P_{L,B} - P_{L,A}}{f_B - f_A} \cdot (f_z - f_A) \tag{G.2}$$

In the third step, the losses in the operating point Z are finally calculated by interpolation between $R1$ and $R2$. As $R1$ and $R2$ have the same horizontal component f_Z by definition, this interpolation is a function of the vertical component iq_Z only:

$$p_{L,Z}(iq_Z) = p_{L,R2} + \frac{p_{L,R1} - p_{L,R2}}{iq_{R1} - iq_{R2}} \cdot (iq_Z - iq_{R2}) \tag{G.3}$$

Inserting the Formulae (G.1) and (G.2) into (G.3) give a final calculation of the losses at the operating point Z in one step:

$$\begin{aligned} & p_{\mathrm{L,Z}}(f_{\mathrm{Z}},iq_{\mathrm{Z}}) = \\ & p_{\mathrm{L,A}} + \frac{p_{\mathrm{L,B}} - p_{\mathrm{L,A}}}{f_{\mathrm{B}} - f_{\mathrm{A}}} \cdot (f_{\mathrm{Z}} - f_{\mathrm{A}}) + \\ & \frac{\left(p_{\mathrm{L,C}} + \frac{p_{\mathrm{L,D}} - p_{\mathrm{L,C}}}{f_{\mathrm{D}} - f_{\mathrm{C}}} \cdot (f_{\mathrm{Z}} - f_{\mathrm{C}})\right) - \left(p_{\mathrm{L,A}} + \frac{p_{\mathrm{L,B}} - p_{\mathrm{L,A}}}{f_{\mathrm{B}} - f_{\mathrm{A}}} \cdot (f_{\mathrm{Z}} - f_{\mathrm{A}})\right)}{iq_{\mathrm{C}} - iq_{\mathrm{A}}} \cdot (iq_{\mathrm{Z}} - iq_{\mathrm{A}}) \end{aligned} \tag{G.4}$$

Taking into account the predefined loss points in Figure 5, the calculation for the segments in Figure G.1 results for segment 1 in:

$$\begin{aligned} & p_{L,Z}(f_Z,iq_Z) = \\ & p_{L,CDM(0,50)} + \frac{p_{L,CDM(50,50)} - p_{L,CDM(0,50)}}{50} \cdot f_Z + \\ & \left(\frac{\left(p_{L,CDM(0,100)} + \frac{p_{L,CDM(50,100)} - p_{L,CDM(0,100)}}{50} \cdot f_Z\right)}{50} - \frac{\left(p_{L,CDM(0,50)} + \frac{p_{L,CDM(50,50)} - p_{L,CDM(0,50)}}{50} \cdot f_Z\right)}{50} \right) \cdot (iq_Z - 50) \end{aligned} \tag{G.5}$$

For Segment 2, the calculation results in:

$$\begin{aligned} & p_{L,Z}(f_Z,iq_Z) = \\ & p_{L,CDM(50,50)} + \frac{p_{L,CDM(90,50)} - p_{L,CDM(50,50)}}{40} \cdot (f_Z - 50) + \\ & \left(\frac{\left(p_{L,CDM(50,100)} + \frac{p_{L,CDM(90,100)} - p_{L,CDM(50,100)}}{40} \cdot (f_Z - 50)\right)}{50} - \frac{\left(p_{L,CDM(50,50)} + \frac{p_{L,CDM(90,50)} - p_{L,CDM(50,50)}}{40} \cdot (f_Z - 50)\right)}{50} \right) \cdot (iq_Z - 50) \end{aligned} \tag{G.6}$$

For Segment 3, the calculation results in:

$$p_{L,Z}(f_Z, iq_Z) = \tag{G.7}$$

$$p_{L,CDM(0,25)} + \frac{p_{L,CDM(50,25)} - p_{L,CDM(0,25)}}{50} \cdot f_Z +$$

$$\left(\frac{\left(p_{L,CDM(0,50)} + \frac{p_{L,CDM(50,50)} - p_{L,CDM(0,50)}}{50} \cdot f_Z \right)}{25} - \frac{p_{L,CDM(0,25)} + \frac{p_{L,CDM(50,25)} - p_{L,CDM(0,25)}}{50} \cdot f_Z}{25} \right) \cdot \left(iq_Z - 25 \right)$$

For Segment 4, the calculation results in:

$$p_{L,Z}(f_Z, iq_Z) = \tag{G.8}$$

$$p_{L,CDM(0,25)} + \frac{p_{L,CDM(50,25)} - p_{L,CDM(0,25)}}{50} \cdot f_Z +$$

$$\left(\frac{\left(p_{L,CDM(50,50)} + \frac{p_{L,CDM(90,50)} - p_{L,CDM(50,50)}}{40} \cdot \left(f_Z - 50 \right) \right)}{25} - \frac{p_{L,CDM(0,25)} + \frac{p_{L,CDM(50,25)} - p_{L,CDM(0,25)}}{50} \cdot f_Z}{25} \right) \cdot \left(iq_Z - 25 \right)$$

G.2.3.2 Numerical calculation for the requested operating point

The requested operating point at 75 % relative motor stator frequency and 80 % torque producing current is in segment 2. Consequently, Formula (G.6) applies. The resulting losses for this operating point are:

$$p_{L,Z}(75{,}80) = 3{,}09 + \frac{3{,}45 - 3{,}09}{40} \cdot \left(75 - 50 \right) + \tag{G.9}$$

$$\left(\frac{\left(4{,}58 + \frac{5{,}91 - 4{,}58}{40} \cdot \left(75 - 50 \right) \right)}{50} - \frac{\left(3{,}09 + \frac{3{,}45 - 3{,}09}{40} \cdot \left(75 - 50 \right) \right)}{50} \right) \cdot \left(80 - 50 \right)$$

$$= 4{,}57$$

The relative losses at 75 % relative motor stator frequency and 80 % relative torque are 4,57 %.

G.2.4 Loss determination by the mathematical model described in 5.2

This way to determine the losses is gives best accuracy. However, it requires all technical parameters for the Formulae (6) to (17). As this data is usually not available in the documentation of a CDM, this calculation method is mainly applicable for CDM manufacturers.

In this calculation example, the parameter values of the evaluated CDM are as follows:

Table G.2 — Parameters of the example CDM

Abbreviation	Description	Example CDM parameter values	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	2,6	V
$U_{D,th}$	Threshold voltage of the power diode	1,1	V
$U_{D,r}$	On state voltage of the power diode at rated CDM output current	2,7	V
$U_{D,th,rectifier}$	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	2,0	V
E_T	Switching loss energy of the power transistor (IGBT) per volt and per ampere	$6{,}5 \cdot 10^{-7}$	$\frac{J}{V \cdot A}$
E_D	Switching loss energy of the power diode per volt and per ampere	$3{,}5 \cdot 10^{-7}$	$\frac{J}{V \cdot A}$
U_{DC}	inverter DC link voltage	540	V
f_{sw}	inverter switching frequency	4000	Hz
I_{cable}	motor cable current, relevant for increased switching losses	10	A
$k1_{choke}$	choke impedance, relative to the nominal inverter impedance	0,03	
$k2_{choke}$	relative voltage drop on the resistive part of the choke	0,25	
λ	input power factor	0,7	
$k1_{DC\_link}$	load independent DC link losses per rated ampere and volt square	$7 \cdot 10^{-7}$	$\frac{1}{\Omega \cdot A}$

Abbreviation	Description	Example CDM parameter values	Unit
$k2_{DC\_link}$	load dependent DC link losses per ampere	1,7	$\Omega \cdot A$
U_{rails}	voltage drop at ohmic conductor elements at rated CDM current	0,7	V
$k_{L,cooling}$	factor for cooling losses	0,15	
$P_{L,control}$	standby and control losses	45	W

The rated phase to phase input voltage of the example CDM is 400V, its rated output current is 14A. Linear interpolation in Table 2 at 80 % torque producing current calculates to a CDM output current of 83,2 % of the rated output current, resulting in 11,65A. Linear interpolation at the same torque producing current in Table 3 gives a power factor of 0,81 at the inverter output.

With this data, the mathematical model described in 5.25.1 can be calculates and gives the following results:

Table G.3 — Results of the CDM calculation according to the mathematical model

Term	Formula	Losses	Unit
On state losses of one inverter transistor	(6)	10,8	W
On state losses of one inverter diode	(7)	2,72	W
Switching losses of one inverter transistor	(8)	13,9	W
Switching losses of one inverter diode	(9)	7,48	W
Output inverter total losses	(10)	209	W
Rectifier losses	(11)	46,8	W
Input choke losses	(12)	45,9	W
DC link losses	(13)	4,59	W
Current rail losses	(14)	6,98	W
Cooling losses	(15)	76,7	W
Overall absolute CDM losses	(16)	435	W
Overall relative CDM losses	(17)	4,37	%

As a conclusion, the relative losses of the example CDM will be determined with the three different evaluation methods to:

Table G.4 — Comparison of different loss evaluation methods

Evaluation method	relative losses
Maximum losses at neighbouring points	5,91 %
Two-dimensional interpolation at neighbouring points	4,57 %
Mathematical model	4,37 %

G.3 Loss determination of the motor

For the example PDS, the losses of a real motor could be measured. In this example, no real motor is assumed to be available, and consequently the reference motor data from Table A.2 for 7,5kW is used.

Table G.5 — Loss data of the 7,5kW reference motor

$P_{r\text{M}}$ / kW	$p_{\text{L,RM}}$, relative (0;25)	$p_{\text{L, RM}}$, relative (0;50)	$p_{\text{L,RM}}$, relative (0;100)	$p_{\text{L,RM}}$, relative (50;25)	$p_{\text{L,RM}}$, relative (50;50)	$p_{\text{L,RM}}$, relative (50;100)	$p_{\text{L,RM}}$, relative (100;50)	$p_{\text{L,RM}}$, relative (100;100)
7,5	2,5	3,7	9,3	4,0	5,3	11,2	7,8	14,7

For the loss calculation, the two-dimensional interpolation model in Formula (G.4) is used. Using the data from the predefined loss points in Table G.5, the motor losses are:

$$p_{L,M}(75{,}80) = 5{,}3 + \frac{7{,}8-5{,}3}{50}\cdot(75-50) + \left(\frac{\left(11{,}2+\frac{14{,}7-11{,}2}{50}\cdot(75-50)\right)}{50} - \frac{\left(5{,}3+\frac{7{,}8-5{,}3}{50}\cdot(75-50)\right)}{50} \right)\cdot(80-50) = 10{,}39\% \tag{G.10}$$

G.4 Loss determination of the PDS

For the loss determination of the PDS, the absolute losses of the CDM and the motor are calculated:

$$P_{L,CDM}(75\%,80\%) = p_{L,CDM(75;80)} \cdot S_{r,equ} = 0{,}0437 \cdot 9{,}95kVA = 435W \tag{G.11}$$

$$P_{L,Mot}(75\%,80\%) = p_{L,M(75;80)} \cdot P_{r,M} = 0.1083 \cdot 7{,}5kW = 812W \tag{G.12}$$

The evaluated operating point is not at rated speed and torque of the PDS. Consequently, the factor x does not apply. For the loss determination of the PDS, the losses of thePDS are calculated according to Formula (27):

$$P_{L,PDS}(75\%,80\%) = 435W + 812W = 1247W \tag{G.13}$$

$$p_{L,PDS}(75\%,80\%) = \frac{1247W}{7500W} = 16{,}63\% \tag{G.14}$$

Annex H
(informative)

Uncertainty of loss determination method

H.1 General

The uncertainty of loss determination method can be specified with a fault tolerance power losses ΔP_L. The intention is to denote the power loss as $P_L = P_{L,\mathrm{determined}} + \Delta P_L$. To calculate the uncertainty, knowledge of all tolerances of the utilized determination method is mandatory. Tolerances can be specified percental in dependence on the measured value or absolute. During calculation of losses, several factors influence the result. Thus, error propagation has to be considered.

H.2 Calculation of uncertainty at randomly occurring errors

For uncertainty calculation under a randomly occurring error assumption, the standard deviation is demanded. Here function *y* represents power loss of CDM or PDS and function y is depending on factors x_i. For the standard deviation s_y under randomly occurring errors and independent factors x_i with standard deviations s_i, it is:

$$s_y = \sqrt{\sum_{i=1}^{n}\left(\frac{\delta y}{\delta x_i} s_i\right)^2} \tag{H.1}$$

Here it is considered, that both positive and negative deviations can occur. Thus for the relative standard deviation it is.

$$\Delta p_L = \frac{\Delta P_L}{P_L} = \frac{s_y}{y} = \frac{\sqrt{\sum_{i=1}^{n}\left(\frac{\delta y}{\delta x_i} s_i\right)^2}}{y} \tag{H.2}$$

H.3 Typical uncertainties for loss determination methods

In Figure H.1, typical uncertainties for different loss determination methods are given. For the calculation and calorimeter it is assumed a constant uncertainty. For input-output method, the uncertainty curve is based on power meter total accuracy of 0,2 % of S_{equ} for the total active power at 50/60 Hz. The curves are based on randomly occurring errors with standard deviation.

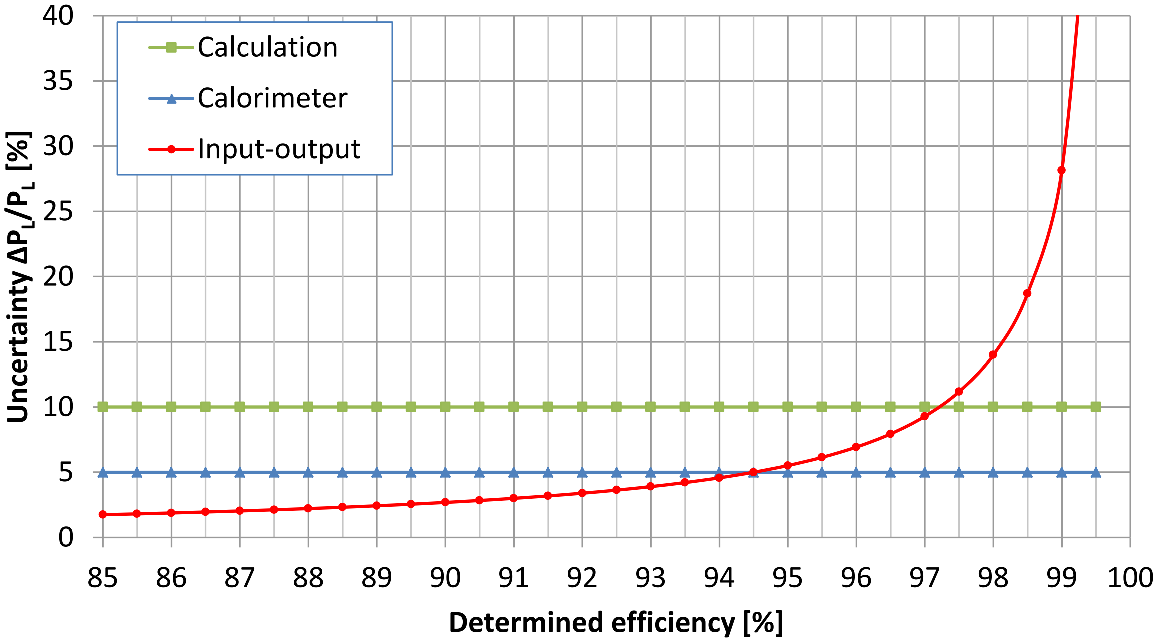


Figure H.1 — Typical standard uncertainties with normal distribution for different CDM and PDS power loss determination methods

Annex I

(informative)

Calorimetric measurement for CDM losses

I.1 General

The calorimetric determination method of the power losses is based on the calorimetric measurement of the dissipated power losses. Measurements shall be done at thermal equilibrium and the component to be measured has to be thermally isolated to guarantee conduction of the dissipated power losses by the cooling medium (air or water). In the following chapters, three different types of methods are explained.

I.2 Calorimeter with two chambers with air as a cooling medium

With the first method, the loss measurement can be carried out in one-phase measurement procedure. Overview of calorimetric test setup is described in Figure I.1. Setup consists of thermally insulated cabinet with two chambers, chamber one is for CDM to be measured and chamber two for the heating resistor. This method requires CDM to be measured and the heating resistor for the calibration to be in the same airflow, and the flow resistance in all test sections shall be equal. Under these conditions, and due to the simultaneity of the measurements, the physical conditions are equal.

From the temperature at the inlet and outlet of the cooling medium to be measured, and between CDM and heating resistor for calibration of its absorbing power loss, the power dissipation can be determined. Power dissipation of measured CDM can be determined by measuring three temperatures and the power of the heating resistor. Heating resistor is supplied by power source with power measurements. All measurements shall be done when thermal equilibrium has been achieved.

$$P_{L,CDM,determined} = P_{L,resistor} \frac{\theta_{inside} - \theta_{in}}{\theta_{out} - \theta_{inside}} \tag{I.1}$$

A variance in air speed, air pressure and air temperature as well as ambient temperature might have an effect on accuracy of the results. It is obvious that the mains voltage is not a constant during measurements. Due to that, some variations will happen in CDM losses. This effect is one of the error sources in this method as well as in other measurements where system is supplied from the uncontrolled mains.

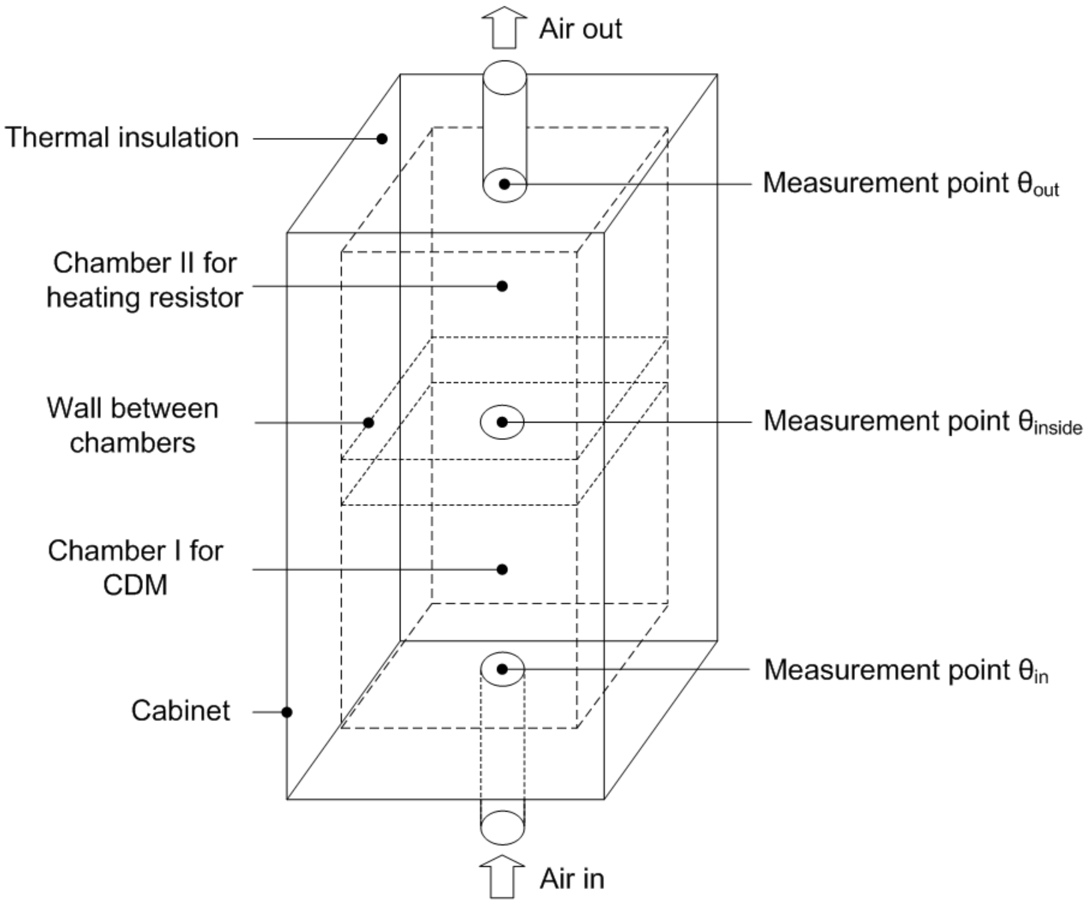


Figure I.1 — One-step calorimetric measurement setup for comparative loss measurement (CDM and heating resistor are loaded simultaneously)

I.3 Calorimeter with one chamber with air as a cooling medium

An alternative calorimetric measurement setup is described in Figure I.2. This setup consists of a thermally insulated cabinet with only one chamber. Both CDM to be measured and the heating resistor for the calibration are located in the same chamber. CDM and resistor are in the same air flow. Two-step setup means that in first step CDM to be measured are loaded and the speed of airflow and temperatures are recorded in thermal equilibrium. In second step the recorded speed of airflow is applied and the heating resistor is loaded so that exactly the same thermal equilibrium as in first step can be achieved. Power dissipation of CDM can be determined from the measured power of heating resistor. Next power loss formula assumes that speed of air flow and temperatures in inlet and outlet are exactly the same in both measuring steps.

$$P_{L,CDM,determined} = P_{L,resistor} \tag{I.2}$$

A variance in air speed, air pressure and air temperature as well as ambient temperature might have an effect on accuracy of the results. It is obvious that the mains voltage is not a constant during measurements. Due to that, some variations will happen in CDM losses. This effect is one of the error sources in this method as well as in other measurements where system is supplied from the uncontrolled mains.

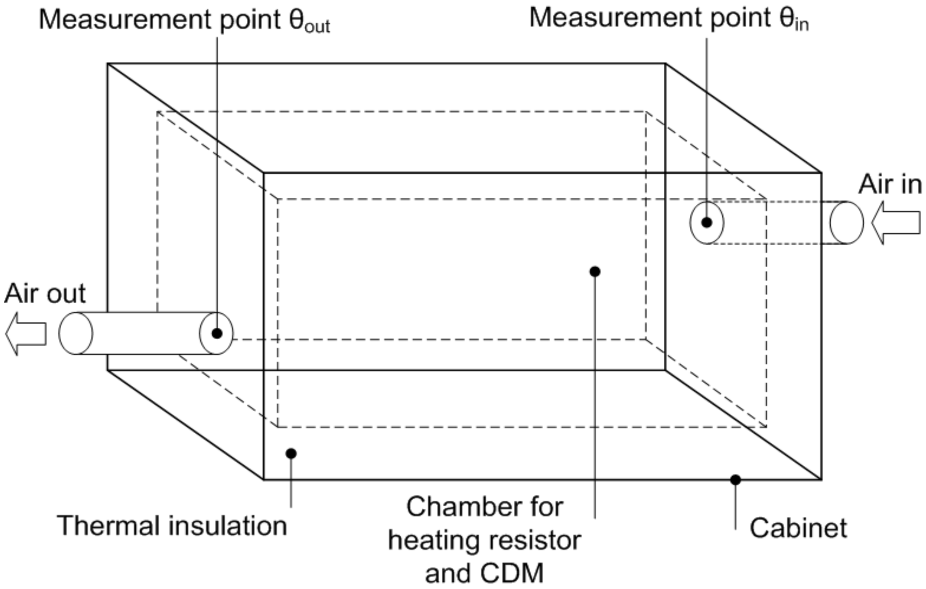


Figure I.2 — Two-step calorimetric measurement setup for comparative loss measurement (CDM and heating resistor are not loaded simultaneously)

I.4 Calorimeter with liquid as a cooling medium

A calorimetric measurement setup with liquid as a cooling medium is described in Figure I.3. This setup consists of a thermally insulated cabinet with one chamber. Inside the chamber there is a cooler which is used to transfer heat power generated by CDM. In the measurement, CDM to be measured are loaded and the volumetric flow rate of liquid and temperatures are recorded in thermal equilibrium. Power dissipation of CDM can be determined according to following formula.

$$P_{L,CDM,determined} = Q_{cooler} \cdot \rho_{liquid} \cdot c_{liquid} \cdot (\theta_{out} - \theta_{in}) \qquad \text{(I.3)}$$

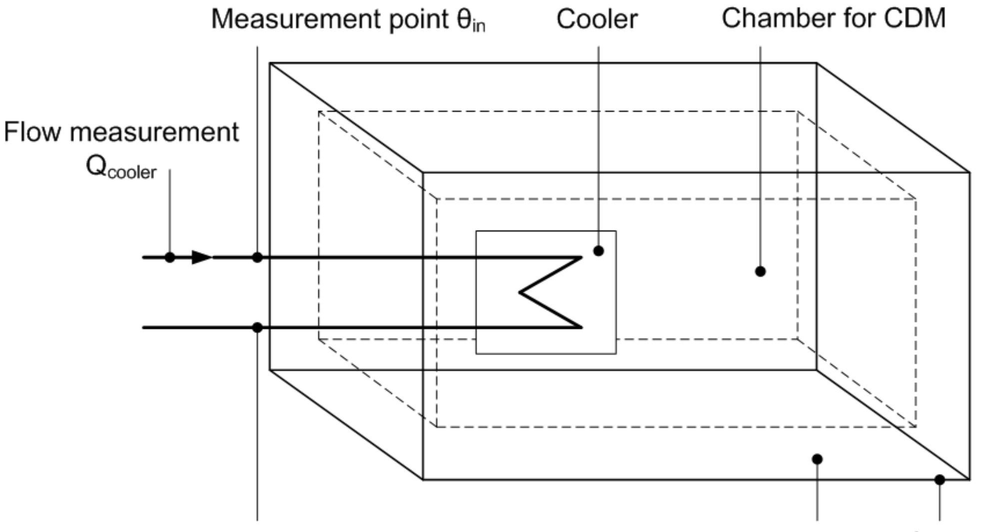
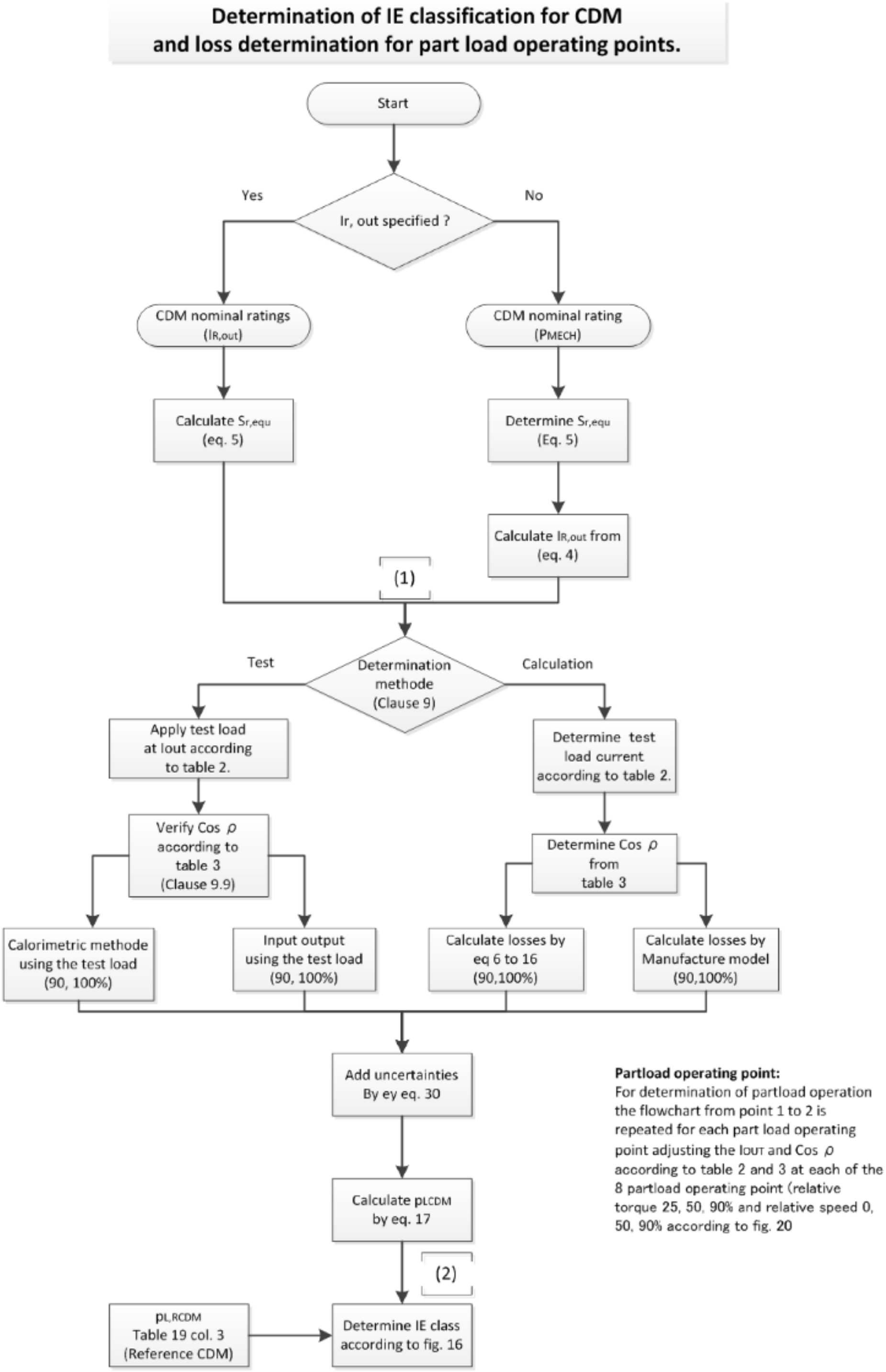


Figure I.3 — Liquid cooled calorimetric measurement setup for CDM loss measurement

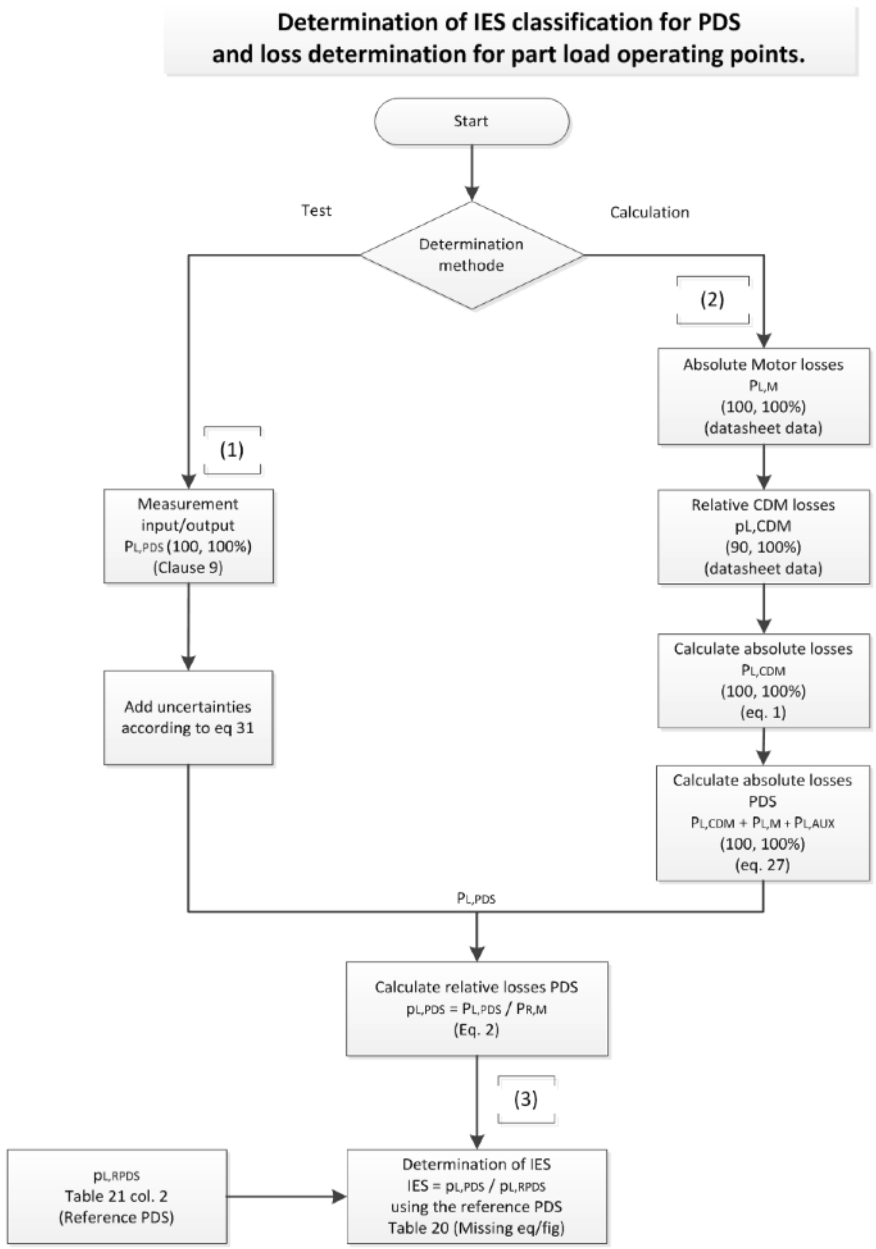
Annex J
(informative)

Flowchart of determination of IE/IES classification for CDM/PDS and loss determination for part load operating points



Partload operating point:
For determination of partload operation the flowchart from point 1 to 2 is repeated for each part load operating point adjusting the I_{OUT} and Cos ρ according to table 2 and 3 at each of the 8 partload operating point (relative torque 25, 50, 90% and relative speed 0, 50, 90% according to fig. 20

Figure J.1 — Determination of IE classification for CDM and loss determination for part load operating points



a) Actual motor might be replaced by Reference motor data. Clause 5.2

b) Actual CDM might be replaced by Reference CDM data. Clause 5.1.

c) For determination of partload operation the test sequence flowchart point (1) – (3) is repeated for each part load operating point adjusting the torque and speed according to figure 2.

d) For determination of partload operation the calculation sequence flowchart point (2) – (3) is repeated for each part load operating point adjusting the torque and speed according to figure 3 and figure 4 for Motor and CDM.

Figure J.2 — Determination of IES classification for PDS and loss determination for part load operating points

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