



BSI Standards Publication

Rotating electrical machines

Part 25: AC electrical machines used in power drive systems — Application guide

National foreword

This Published Document is the UK implementation of CLC IEC/TS 60034-25:2024. It is identical to IEC TS 60034-25:2022. It supersedes PD IEC TS 60034-25:2022, which is withdrawn.

The UK participation in its preparation was entrusted to Technical Committee PEL/2, Rotating electrical machinery.

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

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© The British Standards Institution 2024
Published by BSI Standards Limited 2024

ISBN 978 0 539 31430 4

ICS 29.160.01; 29.160.30

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This Published Document was published under the authority of the Standards Policy and Strategy Committee on 30 November 2022.

Amendments/corrigenda issued since publication

Date	Text affected
31 May 2024	This corrigendum renumbers PD IEC TS 60034-25:2022 as PD CLC IEC/TS 60034-25:2024

English Version

Rotating electrical machines - Part 25: AC electrical machines
used in power drive systems - Application guide
(IEC/TS 60034-25:2022)

Machines électriques tournantes - Partie 25: Machines
électriques à courant alternatif utilisées dans les systèmes
d'entraînement de puissance - Guide d'application
(IEC/TS 60034-25:2022)

Drehende elektrische Maschinen - Teil 25:
Wechselstrommaschinen zur Verwendung in
Antriebssystemen - Anwendungsleitfaden
(IEC/TS 60034-25:2022)

This Technical Specification was approved by CENELEC on 2024-01-22.

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Comité Européen de Normalisation Electrotechnique
Europäisches Komitee für Elektrotechnische Normung

CEN-CENELEC Management Centre: Rue de la Science 23, B-1040 Brussels

European foreword

This document (CLC IEC/TS 60034-25:2024) consists of the text of IEC/TS 60034-25:2022 prepared by IEC/TC 2 "Rotating machinery".

This document supersedes CLC/TS 60034-17:2004 and CLC/TS 60034-25:2008 and all of their amendments and corrigenda (if any).

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Endorsement notice

The text of the International Technical Specification IEC/TS 60034-25:2022 was approved by CENELEC as a European Technical Specification without any modification.

In the official version, for Bibliography, the following notes have to be added for the standard indicated:

IEC 61800-2:2021 NOTE Approved as EN IEC 61800-2:2021 (not modified)

IEC/TR 61800-6 NOTE Approved as CLC/TR 61800-6

Annex ZA (normative)

Normative references to international publications with their corresponding European publications

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

NOTE 1 Where an International Publication has been modified by common modifications, indicated by (mod), the relevant EN/HD applies.

NOTE 2 Up-to-date information on the latest versions of the European Standards listed in this annex is available here: www.cenelec.eu.

<u>Publication</u>	<u>Year</u>	<u>Title</u>	<u>EN/HD</u>	<u>Year</u>
IEC 60034-1	2022	Rotating electrical machines - Part 1: Rating and performance	EN IEC 60034-1	— ¹
IEC 60034-2-1	-	Rotating electrical machines - Part 2-1: Standard methods for determining losses and efficiency from tests (excluding machines for traction vehicles)	EN 60034-2-1	-
IEC 60034-2-2	-	Rotating electrical machines - Part 2-2: Specific methods for determining separate losses of large machines from tests - Supplement to IEC 60034-2-1	EN 60034-2-2	-
IEC 60034-2-3	-	Rotating electrical machines - Part 2-3: Specific test methods for determining losses and efficiency of converter-fed AC motors	EN IEC 60034-2-3	-
IEC 60034-6	-	Rotating electrical machines - Part 6: Methods of cooling (IC Code)	EN 60034-6	-
IEC 60034-9	2021	Rotating electrical machines - Part 9: Noise limits	EN IEC 60034-9	— ²
IEC 60034-12	-	Rotating electrical machines - Part 12: Starting performance of single-speed three-phase cage induction motors	EN 60034-12	-
IEC 60034-14	2018	Rotating electrical machines - Part 14: Mechanical vibration of certain machines with shaft heights 56 mm and higher - Measurement, evaluation and limits of vibration severity	EN IEC 60034-14	2018

¹ To be published. Stage at the time of publication: FprEN IEC 60034-1:2021.

² To be published. Stage at the time of publication: FprEN IEC 60034-9:2021.

CLC IEC/TS 60034-25:2024 (E)

<u>Publication</u>	<u>Year</u>	<u>Title</u>	<u>EN/HD</u>	<u>Year</u>
IEC 60034-18-41	2014	Rotating electrical machines - Part 18-41: Partial discharge free electrical insulation systems (Type I) used in rotating electrical machines fed from voltage converters - Qualification and quality control tests	EN 60034-18-41	2014
+ A1	2019		+ A1	2019
IEC 60034-18-42	2017	Rotating electrical machines - Part 18-42: Partial discharge resistant electrical insulation systems (Type II) used in rotating electrical machines fed from voltage converters - Qualification tests	EN 60034-18-42	2017
+ A1	2020		+ A1	2020
IEC 60079	series	Explosive atmospheres	EN IEC 60079	series
IEC 60079-7	-	Explosive atmospheres - Part 7: Equipment protection by increased safety "e"	EN 60079-7	-
IEC/TR 61000-5-1	-	Electromagnetic compatibility (EMC) - Part 5: Installation and mitigation guidelines - Section 1: General considerations - Basic EMC publication	-	-
IEC/TR 61000-5-2	-	Electromagnetic compatibility (EMC) - Part 5: Installation and mitigation guidelines - Section 2: Earthing and cabling	-	-
IEC 61800-3	-	Adjustable speed electrical power drive systems - Part 3: EMC requirements and specific test methods for PDS and machine tools	EN IEC 61800-3	-
IEC 61800-5-1	-	Adjustable speed electrical power drive systems - Part 5-1: Safety requirements - Electrical, thermal and energy	EN IEC 61800-5-1	-
IEC/TS 61800-8	2010	Adjustable speed electrical power drive systems - Part 8: Specification of voltage on the power interface	-	-
IEC/TS 62578	2015	Power electronics systems and equipment - Operation conditions and characteristics of active infeed converter (AIC) applications including design recommendations for their emission values below 150 kHz	-	-

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

ROTATING ELECTRICAL MACHINES –

**Part 25: AC electrical machines used in power drive systems –
Application guide**

FOREWORD

- 1) The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, IEC publishes International Standards, Technical Specifications, Technical Reports, Publicly Available Specifications (PAS) and Guides (hereafter referred to as “IEC Publication(s)”). Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
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IEC TS 60034-25 has been prepared by IEC technical committee 2: Rotating machinery. It is a Technical Specification.

This fourth edition of IEC TS 60034-25 cancels and replaces the third edition, published in 2014.

This edition includes the following significant technical changes with respect to the previous edition:

- a) The definitions of a converter capable motor and a converter duty motor are added.
- b) Clause 18 modified to include the performance expectations of a converter capable motor.
- c) Clause 8 modified to update shaft currents section.
- d) Annex D added to define the derating requirements.

The text of this Technical Specification is based on the following documents:

Draft	Report on voting
2/2067/DTS	2/2097/RVDTS

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

The language used for the development of this Technical Specification is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/standardsdev/publications.

A list of all parts in the IEC 60034 series, published under the general title *Rotating electrical machines*, can be found on the IEC website.

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

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

IMPORTANT – The 'colour inside' logo on the cover page of this publication indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.

INTRODUCTION

The performance characteristics and operating data for converter-fed electrical machines are influenced by the complete drive system, comprising supply system, converter, cabling, electrical machine, mechanical shafting and control equipment. Each of these components exists in numerous technical variants. Any values quoted in this document are thus indicative only.

In view of the complex technical interrelations within the system and the variety of operating conditions, it is beyond the scope and object of this document to specify numerical or limiting values for all the quantities which are of importance for the design of the power drive system.

To an increasing extent, it is the practice that power drive systems consist of components produced by different manufacturers. The object of this document is to explain, as far as possible, the influence of these components on the design of the electrical machine and its performance characteristics.

This document deals with both AC electrical machines which are specifically designed for converter supply and converter-fed electrical machines within the scope of IEC 60034-12, which are designed originally for mains supply.

ROTATING ELECTRICAL MACHINES –

Part 25: AC electrical machines used in power drive systems – Application guide

1 Scope

This part of IEC 60034 describes the performance characteristics of AC electrical machines for use on converter supplies. For electrical machines specifically designed for converter duty application design features are defined. It also specifies the interface parameters and interactions between the electrical machine and the converter including installation guidance as part of a power drive system, but except for the voltage at the power interface which is described in IEC TS 61800-8.

The general requirements of relevant parts of the IEC 60034 series of standards also apply to electrical machines within the scope of this document.

For electrical machines operating in potentially explosive atmospheres, additional requirements as described in the IEC 60079 series for dust ignition proof apply.

This document is not primarily concerned with safety. However, some of its recommendations may have implications for safety, which are considered as necessary.

Where a converter manufacturer provides specific installation recommendations, they take precedence over the recommendations of this document.

2 Normative references

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

IEC 60034-1:2022, *Rotating electrical machines – Part 1: Rating and performance*

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

IEC 60034-2-2, *Rotating electrical machines – Part 2-2: Specific methods for determining separate losses of large machines from tests – Supplement to IEC 60034-2-1*

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

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

IEC 60034-9:2021, *Rotating electrical machines – Part 9: Noise limits*

IEC 60034-12, *Rotating electrical machines – Part 12: Starting performance of single-speed three-phase cage induction motors*

IEC 60034-14:2018, *Rotating electrical machines – Part 14: Mechanical vibration of certain machines with shaft heights 56 mm and higher – Measurement, evaluation and limits of vibration severity*

IEC 60034-18-41:2014, *Rotating electrical machines – Part 18-41: Partial discharge free electrical insulation systems (Type I) used in rotating electrical machines fed from voltage converters – Qualification and quality control tests*
IEC 60034-18-41:2014/AMD1:2019

IEC 60034-18-42:2017, *Rotating electrical machines – Part 18-42: Partial discharge resistant electrical insulation systems (Type II) used in rotating electrical machines fed from voltage converters – Qualification tests*
IEC 60034-18-42:2017/AMD1:2020

IEC 60079 (all parts): *Explosive atmospheres*

IEC 60079-7, *Explosive atmospheres – Part 7: Equipment protection by increased safety "e"*

IEC TR 61000-5-1, *Electromagnetic compatibility (EMC) – Part 5: Installation and mitigation guidelines – Section 1: General considerations – Basic EMC publication*

IEC TR 61000-5-2, *Electromagnetic compatibility (EMC) – Part 5: Installation and mitigation guidelines – Section 2: Earthing and cabling*

IEC 61800-3, *Adjustable speed electrical power drive systems – Part 3: EMC requirements and specific test methods*

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

IEC TS 61800-8:2010, *Adjustable speed electrical power drive systems – Part 8: Specification of voltage on the power interface*

IEC TS 62578:2015, *Power electronics systems and equipment – Operation conditions and characteristics of active infeed converter (AIC) applications including design recommendations for their emission values below 150 kHz*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

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

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

3.1

bearing voltage ratio

BVR

ratio of the capacitively coupled bearing voltage to the common-mode voltage

3.2**bonding**

electrical connection of metallic parts of an installation together and to ground (earth)

Note 1 to entry: For the purposes of this document, this definition combines elements of IEC 60050-195:2021, 195-01-10 (equipotential bonding) and IEC 60050-195:2021, 195-01-16 (functional equipotential bonding).

3.3**common-mode voltage**

U_{CM}

mean of the instantaneous values of the phase voltages appearing between each phase conductor and earth

[SOURCE: IEC 60050-161: 1990, 161-04-09]

3.4**common-mode current**

i_{CM}

sum of the instantaneous values of the line currents

3.5**converter**

unit for electronic power conversion, changing one or more electrical characteristics and comprising one or more electronic switching devices and associated components, such as transformers, filters, commutation aids, controls, protections and auxiliaries, if any

Note 1 to entry: This definition is taken from IEC 61800-2 and, for the purposes of this document, embraces the terms complete drive module (CDM) and basic drive module (BDM) as used in the IEC 61800 series.

3.6**converter-fed electrical machine**

electrical machine fed from a frequency converter independent of whether it is specifically designed for converter supply or whether it is an electrical machine within the scope of IEC 60034-12, which is designed originally for mains supply

3.7**fixed-speed electrical machine**

electrical machine rated by output power for 50 Hz and/or 60 Hz on-line operation

Note 1 to entry: Fixed-speed electrical machines may be capable of frequency converter operation with variable speed.

3.8**electromagnetic compatibility**

EMC

ability of an equipment or system to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances to anything in that environment

[SOURCE: IEC 60050-161:1990, 161-01-07]

3.9**field weakening**

electrical machine operating mode where electrical machine flux is less than the flux corresponding to the electrical machine rating

3.10**rise time**

time interval between the 10 % and 90 % points of the zero-to-peak voltage (see Figure 12)

3.11**power drive system****PDS**

system consisting of power equipment (composed of converter section, AC electrical machine and other equipment such as, but not limited to, the feeding section), and control equipment (composed of switching control – on/off for example – voltage, frequency, or current control, firing system, protection, status monitoring, communication, tests, diagnostics, process interface/ port, etc.)

3.12**protective earthing****PE**

earthing a point or points in a system or in an installation or in equipment for the purposes of electrical safety

[SOURCE: IEC 60050-195: 2021, 195-01-11, modified: "electrical" added before "safety".]

3.13**skip band**

small band of operating frequencies where steady-state operation of the PDS is inhibited

3.14**surface transfer impedance**

quotient of the voltage induced in the centre conductor of a coaxial line per unit length by the current on the external surface of the coaxial line

[SOURCE: IEC 60050-161:1990, 161-04-15]

3.15**system integrator**

person or organization which brings the components of PDS together according to his scope of supply and has therefore the system responsibility

3.16**rated voltage** **U_N**

root-mean-square value (RMS) of the fundamental line-to-line voltage assigned by the manufacturer for a specified power frequency operating condition of an electrical machine and indicated on its rating plate

3.17**jump voltage**

change in voltage at the terminals of the electrical machine occurring at the start of each impulse when fed from a converter

Note 1 to entry: This is sometime referred to as step voltage.

3.18**converter capable motor**

electric machine designed for direct online start and suitable for operation on a power electronic frequency converter without special filtering

Note 1 to entry: Such motors include but are not limited to IEC Design N, NE, H, or HE, or NEMA Design A, B, or C which may be subject to energy efficiency regulation in the EU, North America or other locations

Note 2 to entry: The intent of the converter capable motor is to run within the thermal class of the insulation system; but as the harmonic content of the converter output voltage varies between different drive topologies, coordination with the manufacturer may be required by the end user.

3.19

converter duty motor

electrical machine designed specifically for operation fed by a power electronic frequency converter with a temperature rise within the specified insulation thermal class or thermal class

Note 1 to entry: Such motors have no IEC Design or NEMA Design letter and are exempt from energy efficiency regulation in the EU, North America and other locations.

4 System characteristics

4.1 General

Although the steps in specifying electrical machine and converter features are similar for any application, the final selections are greatly influenced by the type of application. In this clause, these steps are described, and the effects of various application load types are discussed.

NOTE Converter capable motor are usually IEC Design N, NE, NEY, H, HE, or HEY, covered by IEC 60034-12 or NEMA Design A, B, or C, covered by NEMA MG 1, and may be subject to National energy efficiency regulations (MEPS) in the EU, North American and other locations.

4.2 System information

Complete application information that considers the driven load, electrical machine, converter, and utility power supply, is the best way to achieve the required performance of the entire system. In general, this information should include:

- the power or torque requirements at various speeds;
- the desired speed range of the load and electrical machine;
- the acceleration and deceleration rate requirements of the process being controlled;
- starting requirements including the frequency of starts and a description of the load (the inertia seen at the electrical machine shaft, load torque during starting);
- the duty cycle of the application (a continuous process or a combination of starts, stops, and speed changes; see clause duty in IEC 60034-1);
- a general description of the type of application including the environment in which the PDS components will operate;
- a description of additional functionality that may not be met with the electrical machine and converter only (for example: electrical machine temperature monitoring, ability to bypass the converter if necessary, special sequencing circuits or speed reference signals to control the PDS);
- a description of the available electrical supply power and wiring. The final configuration may be affected by the requirements of the system selected.

4.3 Torque/speed considerations

4.3.1 General

The typical torque/speed characteristics of converter-fed electrical machines, the significant influencing factors and their consequences are shown in Figure 1, Figure 2 and Figure 3. Depending on the performance requirements of the PDS, different electrical machine designs are possible for an adaptation of the individual limiting values.

NOTE Figure 1 to Figure 3 do not show the possible skip bands (see 4.3.8).

4.3.2 Torque/speed capability

Figure 1 shows the torque/speed capability of converter-fed electrical machines. The maximum available torque is limited by the rating of the electrical machine and by the current limitation of the converter. Above the field-weakening frequency f_0 and speed n_0 the electrical machine can operate with constant power with a torque proportional to $1/n$. For induction electrical machines, if the minimum breakdown torque (which is proportional to $1/n^2$) is reached, the power has to be further reduced proportional to $1/n$, resulting in torque proportional to $1/n^2$ (extended range). For synchronous electrical machines, the extended range does not apply. The maximum usable speed $n_{\max}$ is limited not only by the reduction of torque due to field-weakening at speeds above n_0 , but also by the mechanical strength and stability of the rotor, by the speed capability of the bearing system, and by other mechanical parameters. The short-term curves represent the usability of the motor that is commonly needed but does not necessarily represent its maximum capability.

At low frequency, the available torque may be reduced in self-cooled electrical machines to avoid the possibility of overheating.

In some applications, for example with a high moment of inertia, it may be possible to apply a short-time torque boost for starting.

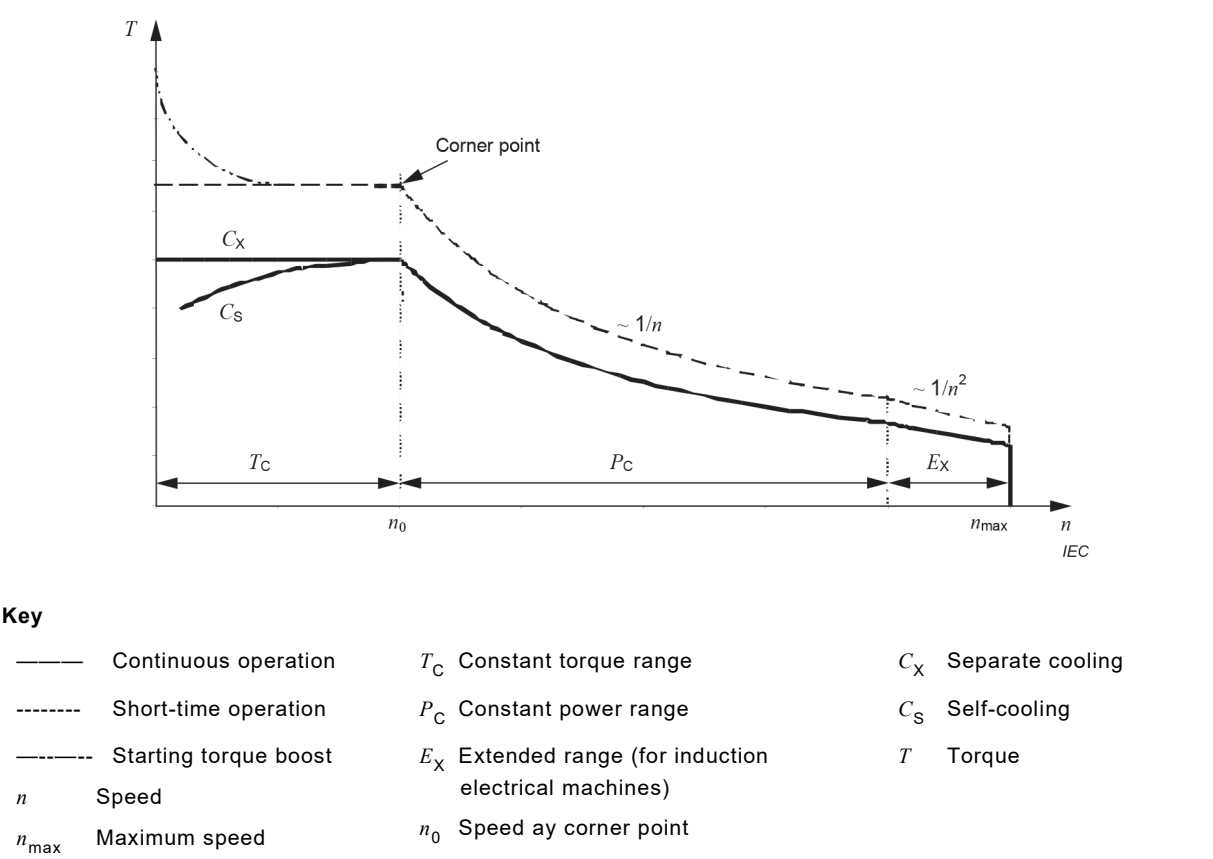
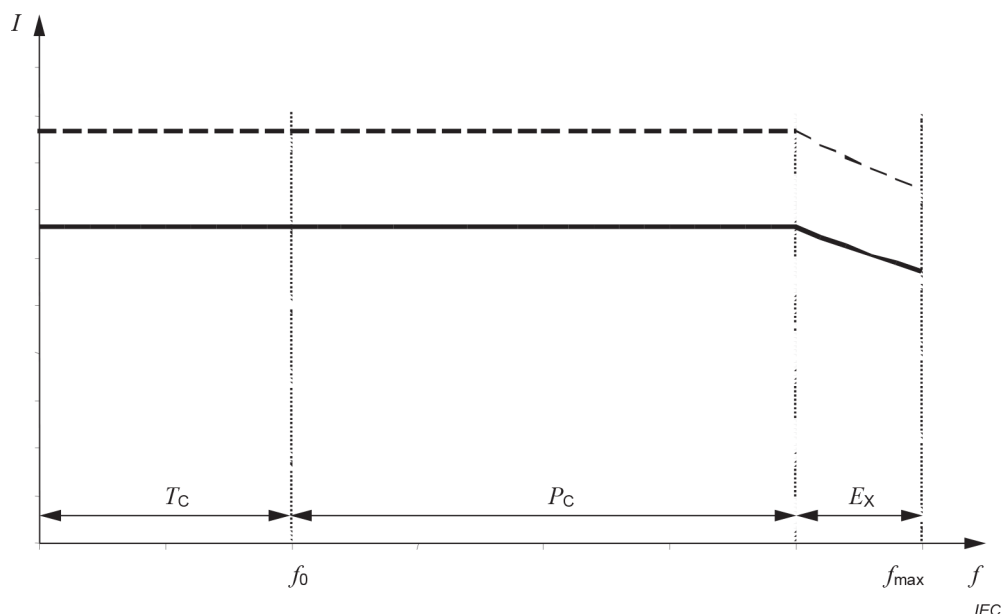


Figure 1 – Torque/speed capability

Figure 2 shows the corresponding converter output current (I) capability.



Key

—	Continuous operation	I	Current
- - - - -	Short-time operation	P_C	Constant power range
f	Speed	E_X	Extended range (for induction electrical machines)
f_0	Speed at corner point	T_C	Constant torque range
		$f_{\max}$	Maximum speed

Figure 2 – Current required by motor

NOTE The current in Figure 2 is shown as constant in the constant power (P_C) range. This would assume that the power factor remains constant. Normally for the current to remain constant, the power will have to be reduced or the current will increase as the load get closer to motor break-down and the power factor reduces.

4.3.3 Electrical machine rating

The rated point, where the electrical machine designed for converter application has its rated speed, rated voltage, rated current, rated torque and rated power, is in general the point where the electrical machine delivers its maximum torque and power, i.e. the point at n_0 corner point in Figure 1 where $n_N = n_0$. The maximum operational speed can be higher than the rated speed and depending on the voltage frequency characteristics (see 4.3.7) the maximum operational voltage can exceed the rated voltage.

4.3.4 Limiting factors on torque/speed capability

The significant factors which influence the torque/speed capability are shown in Table 1.

Table 1 – Significant factors affecting torque/speed capability

Condition	Electrical machine	Converter
Breakaway	Maximum flux capability	Maximum current
Constant flux	Cooling (I^2R losses)	Maximum current
Field-weakening (reduced flux)	Maximum speed (mechanical strength and stability) Maximum torque (breakdown torque)	Maximum voltage
Dynamic response	Equivalent circuit parameters (determined by modelling)	Control capability

4.3.5 Safe operating speed, over-speed capability and over-speed test

For an electric machine, designed for converter application, the capability of converter operation should be indicated on the nameplate. For low voltage cage induction motors the safe operating speed is defined in IEC 60034-1:2022, 9.6.

For motors using hydrodynamics bearings, the minimum safe operating speed should keep a thick-film lubrication on bearing. Below this limit, a hydrostatic system will be necessary. Due to the number of interacting factors relevant for this effect, normally a case-by-case analysis is required, and the manufacturer should verify the practical limits.

The over-speed of AC electrical machines is defined in IEC 60034-1, but an over-speed test is not normally considered necessary. The intention of a test, if specified and agreed, is to check the integrity of the rotor design with respect to centrifugal forces. Although for a fixed-speed electrical machine it is practically impossible to reach an operating speed above its synchronous speed, electrical generators can be accelerated above their synchronous speed by the turbine, for example in case of a sudden load rejection.

For converter-fed electrical machines, an acceleration to a speed higher than the maximum operational speed determined in the control of the converter is unlikely. Especially for large 'super synchronous' electrical machines, it is often beneficial to design an electrical machine for a maximum over-speed of 1,05 times the maximum operation speed. Test may also be performed at 1,05 times maximum operating speed. There is no technically justified argument against such agreement.

It should be appreciated that with high speed running fine balancing of the rotor may be required. If the high speed is required for more than short periods the bearing life may be reduced. Also, for high-speed applications, special attention should be paid to both the grease service life and the re-greasing interval.

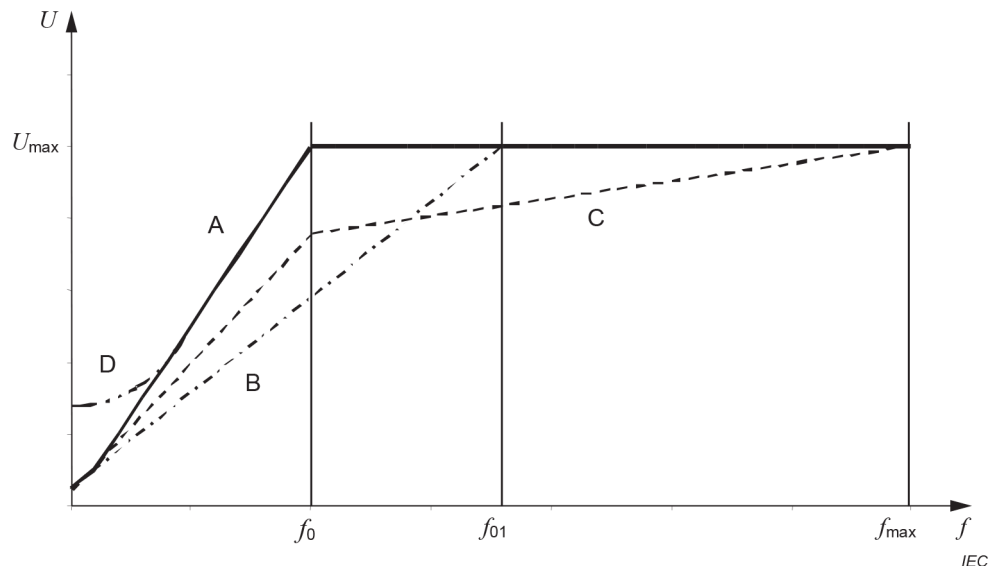
4.3.6 Cooling arrangement

As Figure 1 indicates, the type of cooling influences the maximum torque/speed capability of PDS. Electrical machines with power ratings in the megawatt range often have a cooling arrangement consisting of a primary cooling circuit (usually with air as primary coolant) and a secondary cooling circuit (with air or water as secondary coolant). The losses are transferred via a heat exchanger from the primary into the secondary circuit.

- Where both primary and secondary coolants are moved by a separate device, and their flow is thus independent of the electrical machine's rotor speed (for example, IC656 according to IEC 60034-6), the curve in Figure 1 for separate cooling applies.
- Where the secondary coolant is moved by a separate device and the primary coolant by a shaft-driven device (for example, IC81W or IC616), the curve in Figure 1 for self-cooling applies.
- Where both primary and secondary coolants are moved by a shaft driven device, the output torque should not exceed the curve $T/T_N = n^2/n_0^2$ and the minimum operational speed is recommended to be $\geq 70\%$ of rated speed.

4.3.7 Voltage/frequency characteristics

The relationship between the converter output voltage (U) and frequency can have several characteristics, as shown in Figure 3.



Key

- A The voltage increases with frequency, and the maximum converter output voltage $U_{\max}$ is achieved at the field-weakening frequency f_0 .
- B The voltage increases with frequency, and the maximum converter output voltage $U_{\max}$ is achieved above f_0 at a new field-weakening frequency f_{01} . This provides an extended speed range at constant flux (constant torque), but the available torque in this speed range is less than that of case A.
- C The voltage increases with frequency up to f_0 , and then increases at a lower rate, the maximum converter output voltage $U_{\max}$ being achieved at $f_{\max}$. This avoids excessive torque reduction in the constant flux range.
- D A voltage boost is applied at very low frequencies to improve starting performance, and to prevent an unwanted increase in current.

In all these cases, the voltage/frequency dependence may be linear or non-linear, according to the torque-speed requirements of the load.

Figure 3 – Examples of possible converter output voltage/frequency characteristics

4.3.8 Resonant speed bands

The speed range of a converter-fed electrical machine may include speeds that can excite resonances in parts of the electrical machine stator, in the electrical machine/load shaft system or in the driven equipment. Depending on the converter, it may be possible to skip the resonant frequencies. However, even when resonant frequencies are skipped, the load will be accelerated through that speed if the electrical machine is set to run at any speed above this resonant speed. Decreasing the acceleration time can help minimize the time spent in resonance. The speed range shall be agreed with machine manufacturer.

4.3.9 Duty cycles

4.3.9.1 General

Cyclic duty applications are those in which transitions between speeds or loads are common (see IEC 60034-1). Several aspects of this type of application affect the electrical machine and the converter.

- Electrical machine heat dissipation is variable, depending on rotation speed and cooling method.
- Torque demands above electrical machine full-load torque may be required. Operation above electrical machine full load torque may be required to accelerate, handle peak loads, and even decelerate the load. Operation above electrical machine rated current will increase electrical machine heating. This may require a higher thermal class of insulation, an electrical machine rated for the overload, or evaluation of the duty cycle to determine if the electrical machine has enough cooling for the application (see IEC 60034-1, duty type S10).
- DC injection, dynamic, or regenerative braking may be required to reduce the electrical machine speed. Regardless of whether the electrical machine is generating torque to drive the application, generating power back to the converter due to the electrical machine being driven by the load, or supplying braking torque during deceleration by applying d.c. current to the windings, electrical machine heating takes place approximately proportionally to the square of the current while applied. This heating should be included in the duty cycle analysis. Furthermore, the transient torques imposed on the shaft by braking should be controlled to a level that will not cause damage.

NOTE IEC TR 61800-6 provides information on load duty and current determination for the entire PDS.

4.3.9.2 High impact loads

High impact loads are a special case of duty and are encountered in certain intermittent torque applications (for example, IEC 60034-1, duty type S6). In these applications, the load is applied or removed from the electrical machine very quickly. It is also possible for this load torque to be positive (against the direction of rotation of the electrical machine) or negative (in the same direction as electrical machine rotation).

The impact load will result in a rapid increase or decrease in current demand (from the converter). If the torque is negative, the electrical machine may generate current back into the converter. These transient currents create stresses in the stator winding. The magnitude of these transient currents is a function of the size of the converter and of the electrical machine.

4.4 Electrical machine requirements

NOTE This subclause refers mainly to induction electrical machines, but some of the requirements may also be relevant for other electrical machine types.

Table 2 indicates some main individual aspects and design considerations.

Table 2 – Electrical machine design considerations

Required aspect of application	Design consideration
Long-term operation at low speed	Thermal over sizing or independent cooling. For long-term operation of sleeve bearings below 10 % of corner point speed, the bearing performance should be confirmed by the manufacturer. Consideration should be given to the type of grease and greasing intervals.
Large ratio of speeds	Cooling independent of speed (separate fan, or other cooling medium, for example, water)
Speed feedback device	Precautions for mechanical interface. Speed sensor may need to be electrically insulated
High speed (field-weakening)	Mechanical aspects. High breakdown torque (i.e. small leakage reactance). U/f characteristic is constant until $f > f_0$ (see Figure 3)
Improved electrical machine efficiency with converter supply	Rotor cage designs (rotor bars with less skin effect are preferred, see 5.2). May adversely affect line starting capability
Line bypassing or line start capability	Rotor cage design shall be appropriate. Consequently the design may not be optimized to reduce losses and improve efficiency – balanced compromise necessary
High breakaway torque	If possible, increase flux by 10 % to 40 % (depending on electrical machine size) at near-zero frequencies
Voltage drop in the converter because of modulation or filter or cabling	Adaptation of the rated electrical machine voltage to compensate for the voltage drop, i.e. the rated voltage of the electrical machine can be lower than the supply voltage to the converter.
Multi-electrical machine operation at approximately synchronized common speed	Similar slip/torque characteristics of the electrical machines

In some applications, the electrical parameters of the electrical machine equivalent circuit (see Table 3 for examples) may be requested from the electrical machine designer for tuning the converter.

Table 3 – Electrical machine parameters for the tuning of the converter

Parameter	Description/explanation	Scalar control	Vector or direct flux and torque control
Maximum values			
Maximum speed		Yes	Yes
Maximum temperatures of the stator and rotor windings		Yes	Yes
Acoustic parameters			
Frequencies which should be skipped by the converter, to avoid acoustic and electrical machine resonances		Yes, if discrete carrier frequencies occur	
Mechanical parameters			
Inertia	For high rates of acceleration	Optional	Optional
Coefficients k_1 and k_2 of friction and cooling fan torque demand ($T = k_1 \times n + k_2 \times n^2$)	For some factory automation or production tasks, when accurate determination of mechanical output power is required	Optional	Optional
Electrical parameters of the T-equivalent circuit diagram for induction electrical machines			
Stator resistance (R_s)	At operating temperature	Optional for IR compensation	Yes
Rotor resistance (R_r') (see NOTE 1)	At rated operating point and temperature, different from locked rotor condition	Optional for advanced scalar control	Yes
Stator leakage reactance ($X_{\sigma s}$)	At corner point frequency	Optional for advanced scalar control	Yes
Rotor leakage reactance ($X_{\sigma r}'$) (see NOTE 1)	At rated operating point, different from locked-rotor condition	Optional for advanced scalar control	Yes
Magnetizing reactance (X_m)	At corner point frequency and rated operating point	Optional for advanced scalar control	Yes
Magnetizing conductance (G_m)	At corner point frequency and rated operating point	Optional for advanced scalar control	Yes
Magnetizing inductance as a function of voltage.	For field-weakening	Yes, for advanced scalar control	Yes
Lateral critical speed if below maximum operational speed	Speed to be avoided for continuous operation	Yes	Yes
Rotor skin effect, (e.g. ladder equivalent circuit)	For accurate determination of harmonic losses and temperature rise in applications where rapid current response and precise dynamic control is required	Optional	Optional
Stator skin effect		Optional	Optional
NOTE 1 The rotor electrical parameters R_r' and $X_{\sigma r}'$ are as referred to the stator circuit.			
NOTE 2 Some converters do not require motors resistance and reactance values for tuning purposes, as those determine required parameters by themselves.			

Consideration shall be given also to torsional critical speeds where continuous operation at these speeds shall also be avoided.

For improved thermal modelling, or in applications where high torque with precise control is required at low speeds, it may also be useful for the electrical machine designer to supply data on the internal thermal capacitances and resistances of the component parts of the electrical machine. These parameters may be dependent on both rotational and switching frequency.

5 Losses and their effects (for induction electrical machines fed from voltage source converters)

5.1 General

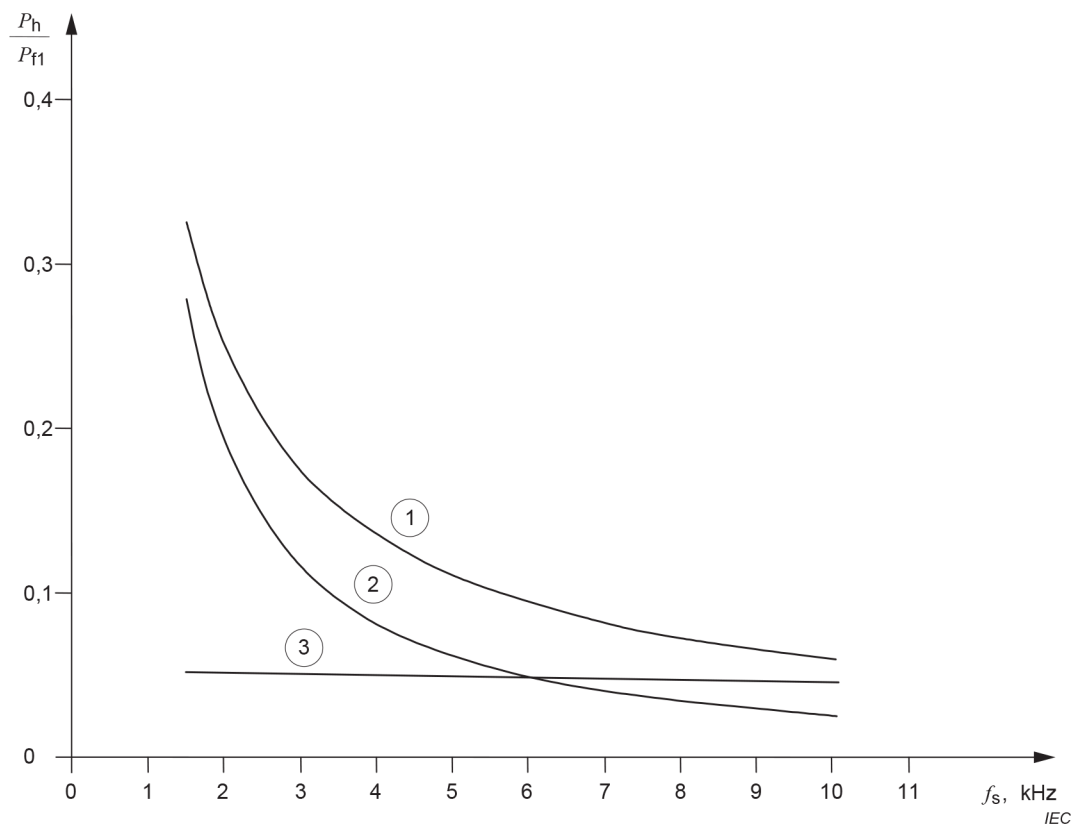
In the case of voltage source converters, a knowledge of the electrical machine equivalent circuit is normally not important for the design of the commutating circuit, but the harmonic impedances of the electrical machine greatly influence the losses caused by harmonics. Voltage source converters impress their output voltage on the associated electrical machines. The output voltage synthesizes a sinusoidal wave using quasi-rectangular voltage pulses, having steep slopes and approximately constant amplitude (two-level converters impress a peak-to-peak value of the intermediate DC voltage).

In addition to the well-known losses due to fundamental voltage and current, the non-sinusoidal supply by a converter creates additional losses in the electrical machine. These additional losses depend on speed, voltage and current, the converter output voltage waveform, and the design and size of the electrical machine. If neither series inductances nor filters are provided, these losses can amount up to around 10 % to 30 % of the fundamental losses for two-level converters and thus up to about 1 % to 2 % of the rated output of the electrical machine, decreasing with increasing electrical machine size. For three-level converters, the additional losses due to converter supply are lower, typically 0,2 % to 1 % of rated output.

The magnitude and the characteristic behaviour of the additional losses due to converter supply depend on the design of the electrical machine, the type and parameters of the converter, and the use of filter circuits.

The total value of the additional losses caused by harmonics decrease with increasing switching frequency (see Figure 4). This effect is caused by the small additional winding losses at high switching frequencies.

See Annex A for converter types and characteristics.



Key

- 1 Total harmonic losses
- 2 Harmonic winding losses
- 3 Harmonic iron losses

Figure 4 – Example for the dependence of the electrical machine losses caused by harmonics P_h , related to the losses P_{f1} at operating frequency f_1 , on the switching frequency f_s in case of 2 level voltage source converter supply

5.2 Location of the additional losses due to converter supply and ways to reduce them

For the converter output pulses the electrical machine appears as a frequency-dependent impedance. The losses of this impedance are mostly due to skin effect in the conductors (mainly the rotor bars, but in some cases also the stator conductors) and to eddy currents in the leakage flux paths (especially in the laminations).

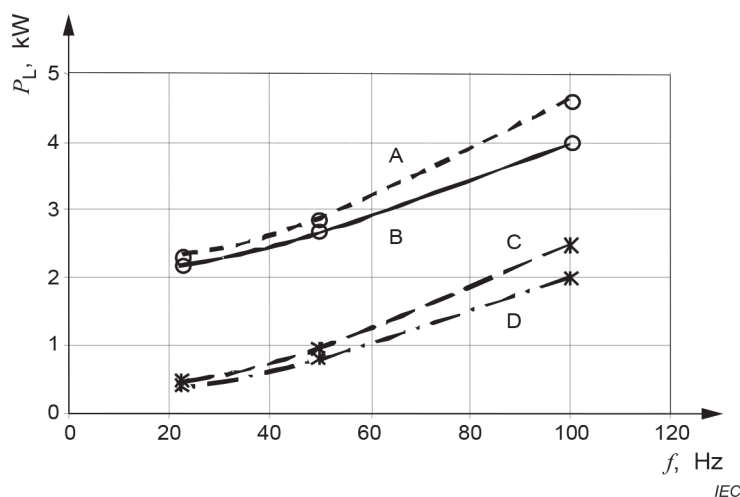
The additional losses due to converter supply can be minimized by various design measures, **either internal or external to the motor**, for example:

- rotor winding design with less skin effect;
- stator winding design with less skin effect;
- open rotor slots;
- avoidance of short-circuits between the rotor laminations;
- thinner stator and rotor laminations, to reduce eddy-current losses;
- **and external to motor** reduced eddy current losses in series inductors or filters.

5.3 Converter features to reduce the electrical machine losses

5.3.1 Reduction of fundamental losses

Figure 5 shows examples of the losses at no-load and at full-load for a 37 kW, 50 Hz electrical machine powered from sinusoidal and 5,5 kHz voltage source converter supplies. It can be seen that the additional losses due to PWM supply are small compared with the fundamental losses.



Key

- | | | | |
|-------------------------|--------------------------------|-----------------------|------------------------------|
| A Full load, PWM supply | B Full-load, sinusoidal supply | C No load, PWM supply | D No load, sinusoidal supply |
|-------------------------|--------------------------------|-----------------------|------------------------------|

Figure 5 – Example of measured losses P_L as a function of frequency f and supply type

The most significant benefits of converter supply are achieved by optimizing the electrical machine flux depending on load (for example, reduction of flux at partial load) since this reduces the fundamental losses which are considerably higher than the additional losses. This “flux optimization” is frequently used in pump and fan applications for which the required torque is proportional to the square of the speed. At lower speeds the torque is considerably reduced and can therefore be created with lower flux and with lower losses in the electrical machine.

The same principle is used in the “constant power factor control” in applications where the load torque varies (not necessarily the speed) by adjusting the electrical machine flux according to the need so that the electrical machine current power factor stays at the optimum value.

The fundamental losses may also be reduced by variation of the intermediate DC voltage. Higher DC link voltage may also help to decrease over-modulation.

5.3.2 Reduction of additional losses due to converter supply

The additional losses due to converter supply may be reduced by reducing the harmonic content of the converter output voltage by, for example:

- optimizing the pulse patterns;
- increasing the switching frequency; typically, the additional losses due to converter supply in the electrical machine show a strong decline with increasing pulse frequency up to a few kHz (see Figure 6). However, the commutation losses in the converter increase with the pulse frequency (see Figure A.1) with the result that the sum of the losses has a minimum at a few kHz. For hysteresis or random PWM controlled converters, an average switching frequency applies which may also depend on voltage and current;
- multi-level converter configuration.

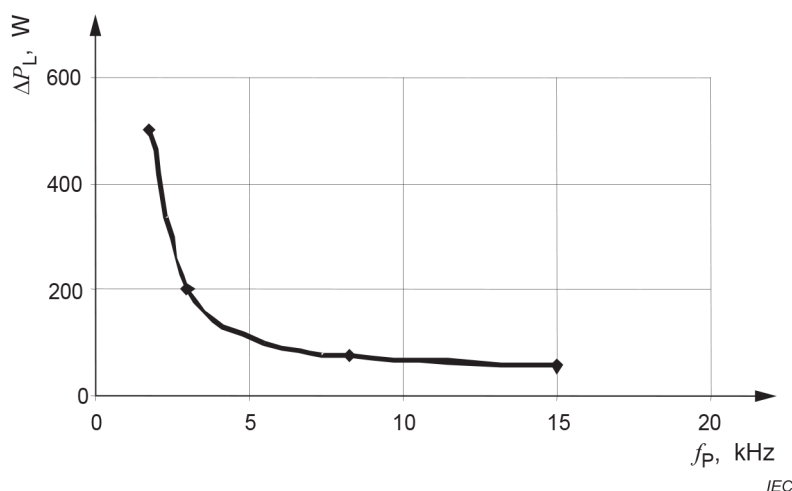


Figure 6 – Additional losses ΔP_L of an electrical machine (same electrical machine as Figure 5) due to converter supply, as a function of pulse frequency f_p , at 50 Hz rotational frequency

5.4 Use of filters to reduce additional electrical machine losses due to converter supply

Filters may be used at the output from a converter to reduce the amplitude and du/dt of the high-frequency switching voltage without excessively affecting the low-frequency resultant voltage appearing at the electrical machine terminals. The total effects will depend on the application and dimensioning of the electrical machine and the filter. The voltage drop across the filter will reduce the voltage at the electrical machine terminals, and this should be taken into account in order to avoid an increase in the fundamental current loss in the electrical machine. Also, there will be some losses in the filter, but these will generally be lower than the reduction of additional electrical machine losses due to converter supply, and so the overall efficiency of the PDS will improve.

In addition to reducing the additional electrical machine losses due to converter supply, such filters may also have a beneficial effect in reduced voltage stress on the electrical machine windings, decreased torque ripple, and improved EMC performance (see 9.2). However, there will be a slowing of the dynamic response of the PDS, and there may be other limitations due to the voltage drop across the filter.

5.5 Temperature influence on life expectancy

The sum of the fundamental and additional losses due to the load condition and the voltage waveform results in a temperature rise of the electrical machine windings. The temperature rise will also be affected by a change in cooling at the operating point within the specified speed range.

There are several ways to take this effect into account, for example:

- use of a separate cooling supply, such as IC0A6 or IC1A7 (see IEC 60034-6) for an air-cooled electrical machine;
- use of a higher thermal insulation class (see IEC 60034-1);
- full compensation for the intended operating ambient temperature (see IEC 60034-1);
- use of oversized electrical machine;
- optimization of converter output waveform.

NOTE Increased temperatures may affect not only the winding insulation ageing but also the bearing lubrication, and hence the bearing lifetime.

The influence of variable load and speed on the winding temperature is characterized by the duty type as defined in IEC 60034-1. The most suitable duty types for converter-fed electrical machines are S1 and S10. Duty type S1 considers the maximum permitted temperature, whereas S10 (for operation at varying load and speed) permits temperature rises which exceed the limit values of the thermal class for limited periods. Limit values of temperature rise are given in IEC 60034-1:2022, and Annex A of that standard gives a formula for the estimation of thermal life expectancy.

5.6 Determination of electrical machine efficiency

The recommended methods to determine the electrical machine efficiency on sinusoidal supply are given in IEC 60034-2-1 and IEC 60034-2-2. For voltage converter fed cage induction motors a new method to determine harmonic losses is described in IEC TS 60034-2-3.

If practical, if required to achieve a more accurate assessment of the overall losses (including the additional harmonic losses), they should be determined with the behaviour of the final PDS.

6 Acoustic noise, vibration and torsional oscillation

6.1 Acoustic noise

6.1.1 General

The converter and its function create three variables which directly affect emitted noise. They are:

- changes in rotational speed which may range from near zero speed to values in excess of the corner point speed. The components and factors that influence noise emissions are bearings and lubrication, ventilation and any other features that are affected by temperature changes;
- electrical machine power supply frequency and harmonic content which have a large effect on the magnetic noise excited in the stator core and, to a lesser extent, on the bearing noise;
- torsional and radial excitations of the stator core due to the interaction of waves of different frequencies of the magnetic field in the electrical machine air gap.

6.1.2 Changes in noise emission due to changes in speed

6.1.2.1 Sleeve (or plain) bearings

There will be no significant change in the noise level emitted by plain bearings.

6.1.2.2 Rolling element bearings

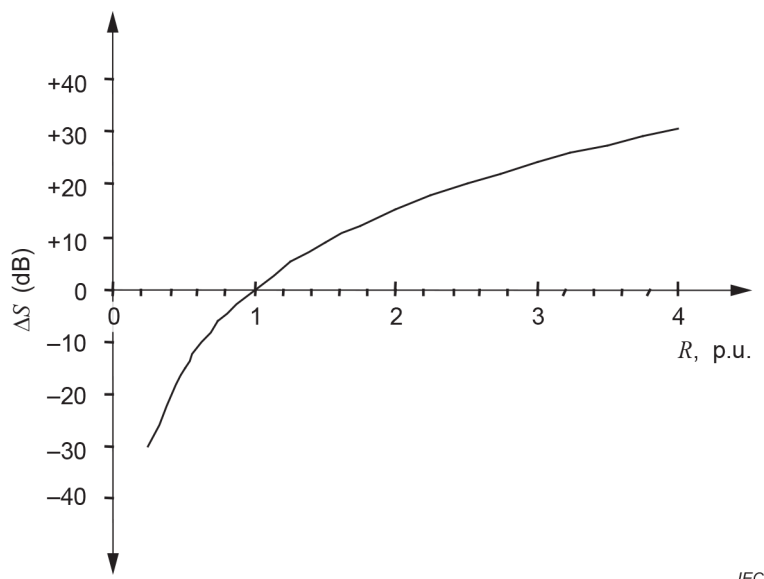
The fundamental frequencies of potential noise emission from a rolling element bearing will vary directly with the rotational speed. If the bearing is "quiet" at the corner point speed, it is unlikely for the noise level to change significantly when the speed is reduced. However, when the speed is increased above the corner point speed there is the possibility that the noise level could increase dramatically due to harmonics of the fundamental frequencies growing due to skidding of the rolling elements. The susceptibility to this phenomenon has been shown to increase rapidly at speed factors (bearing diameter in mm × rotational speed in r/min) greater than 180 000. Experience has shown that the noise level increase can be countered by increasing the lubricant supply to the bearing by regreasing at very short intervals or by utilising oil bath or oil mist lubrication.

When operating at the highest speeds in the electrical machine's range, the bearing temperature will be higher than running at lower speeds. It is important therefore to ensure that adequate nominal clearance and/or a spring-loaded arrangement is embodied in the design.

Grease lubricated bearings will perform perfectly satisfactorily at low operating speeds.

6.1.2.3 Ventilation noise

For a shaft-mounted fan, the noise generated will vary approximately as the characteristic shown in Figure 7 (for a fan peripheral velocity up to 50 m/s). The fan noise $S(\text{dB})$ will decrease per the following formula $\Delta S(\text{dB}) = 50 \cdot \log_{10}(R)$ or by about 15 dB for a 50 % reduction in speed and increase by about 9 dB for a speed increase of 50 %. If the drive is unidirectional, very effective noise reduction can be achieved by utilising a fan on the electrical machine with unidirectional fan (axial or centrifugal).



IEC

Key

ΔS Change in sound pressure

R Fan speed p.u.

$$\Delta S(\text{dB}) = 50 \cdot \log_{10}(R)$$

Figure 7 – Relative fan noise as a function of fan speed

6.1.3 Magnetically excited noise

Magnetic noise is essentially caused by waves of tensile stress acting in the radial direction on the stator core at the air gap. These so-called Maxwell forces are excited by the interaction of the various magnetic fields in the air-gap. The tensile stress is characterized by its amplitude, frequency and mode. As the amplitudes are small, the tensile stress results in disturbing tones only when frequency and mode of a specific wave coincides with the frequency and mode of a natural frequency of the stator core.

In the case of sinusoidal supply voltages, the magnetic noise is caused by the spatial harmonics of the air-gap field. The aim of a professional design is to avoid resonances at the rated operating conditions of the electrical machine. But, because of the large variety of contributing spatial harmonic fields, audible magnetic noise is unavoidable at specific speeds, when the electrical machine is operated at constant flux over a wide speed setting range, even when the supply voltage is sinusoidal. Skipping of a small frequency band is frequently used to avoid a too high noise emission at the associated speed. This means this effect is not associated with the converter supply and would also occur in case of variable-frequency sinusoidal supply voltages.

The statements given above are valid also when an electrical machine is supplied from a converter. But, in this case, the magnetic fields produced by the time harmonics are superimposed. With respect to considerable magnetic noise, it is sufficient to consider the interaction of the fundamental air-gap fields (number of pole pairs p) of the operating frequency and the different harmonics. Therefore, the additionally generated waves of tensile stress are of the modes $r = 0$ and $r = 2p$. The natural frequencies of these modes depend on the size and the design of the electrical machine

The objective of PDS designers is to create optimum noise solutions, but it should be recognized that such solutions are not the responsibility of either the converter designer or the electrical machine designer alone and that in many cases design co-operation is essential.

Experience has shown that with pulse frequencies less than 3 kHz, the harmonic frequencies can be close to the natural frequencies of the electrical machine core and structure on medium and large electrical machines and consequently with wide speed range applications, resonance points are nearly unavoidable at some point in the speed range (see Figure A.2). The resonance frequencies for the modes $r = 0$ and $r = 2p$ (see Figure 8 for illustrations of modes $r = 0, 2$ and 4) are less than 2,5 kHz for 2-pole and 4-pole electrical machines with shaft height greater than 315 mm. By contrast, the trend to increase the converter pulse frequency to 4 kHz or 5 kHz or even higher will result in possible resonance occurring on progressively smaller electrical machines.

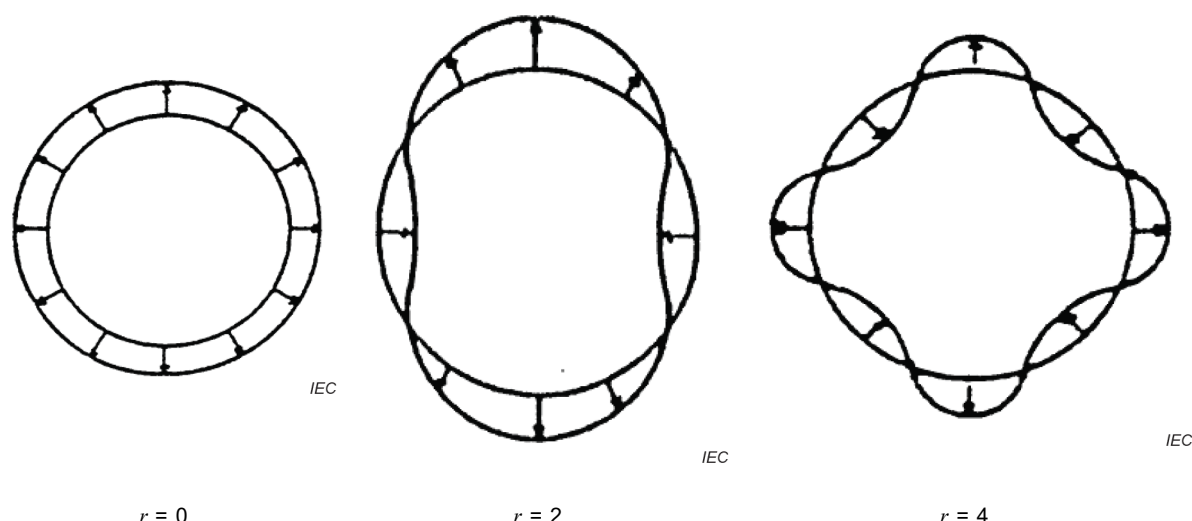


Figure 8 – Vibration modes of the stator core

The increment of noise of electrical machines supplied from PWM controlled converters compared with the same electrical machine supplied from a sinusoidal supply is relatively small (a few dB(A) only) when the switching frequency is above about 3 kHz. For lower switching frequencies, the noise increase may be tremendous (up to 15 dB(A) by experience). Some advanced PWM or hysteresis-controlled converters no longer use fixed carrier frequencies and therefore produce a widely spread spectrum of non-fundamental frequencies. Thus, the typical noise increase and the subjective audible noise can be drastically reduced.

It may be necessary to create "skip bands" in the operating speed range in order to avoid resonance conditions.

For an indication of the noise increase when operated on a converter see IEC 60034-9:2021, Annex B (informative).