IEC TS 60034-25

Edition 4.0 2022-06

TECHNICAL SPECIFICATION

colour inside

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

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INTERNATIONAL
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CONTENTS

INTERNATIONAL ELECTROTECHNICAL COMMISSION

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ROTATING ELECTRICAL MACHINES –

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

FOREWORD

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- withdrawn,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.

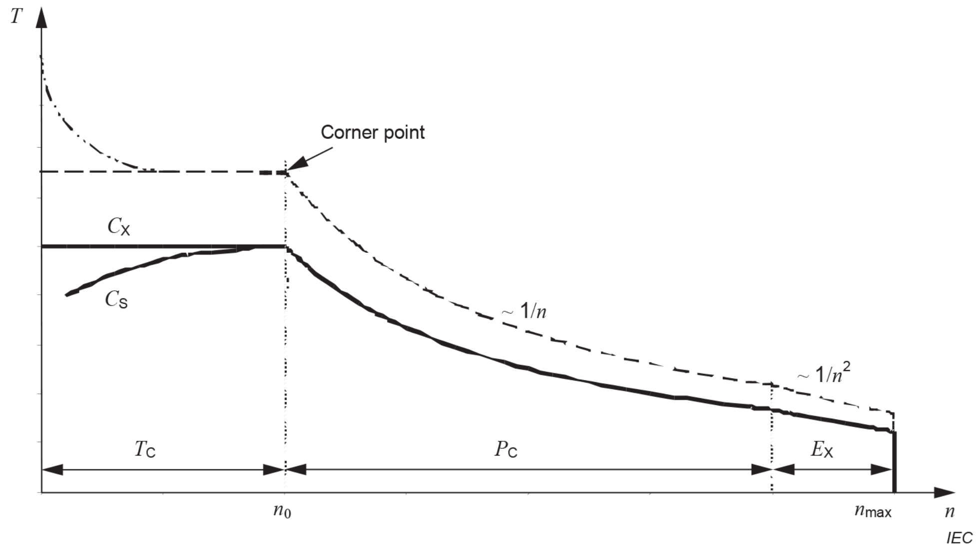
NOTE Figure 1 to Figure 3 do not show the possible skip bands (see 4.3.8).

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.

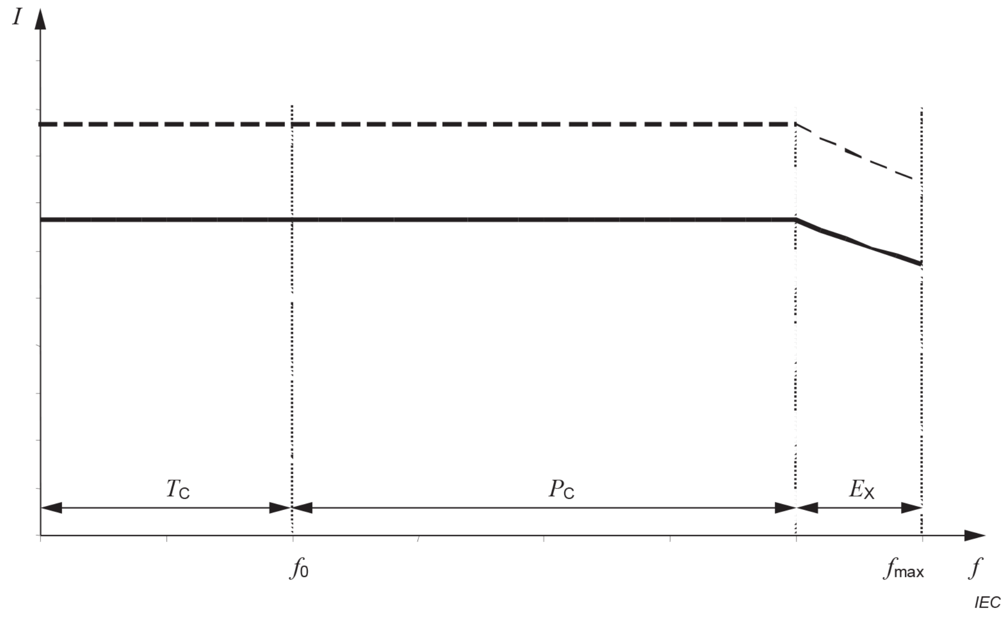


Key

———	Continuous operation	T_C	Constant torque range	C_X	Separate cooling
--------	Short-time operation	P_C	Constant power range	C_S	Self-cooling
—·-·—·-	Starting torque boost	E_X	Extended range (for induction electrical machines)	T	Torque
n	Speed	n_0	Speed ay corner point		
n_{max}	Maximum speed				

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)	T_C	Constant torque range
f_0	Speed at corner point			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_o 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.

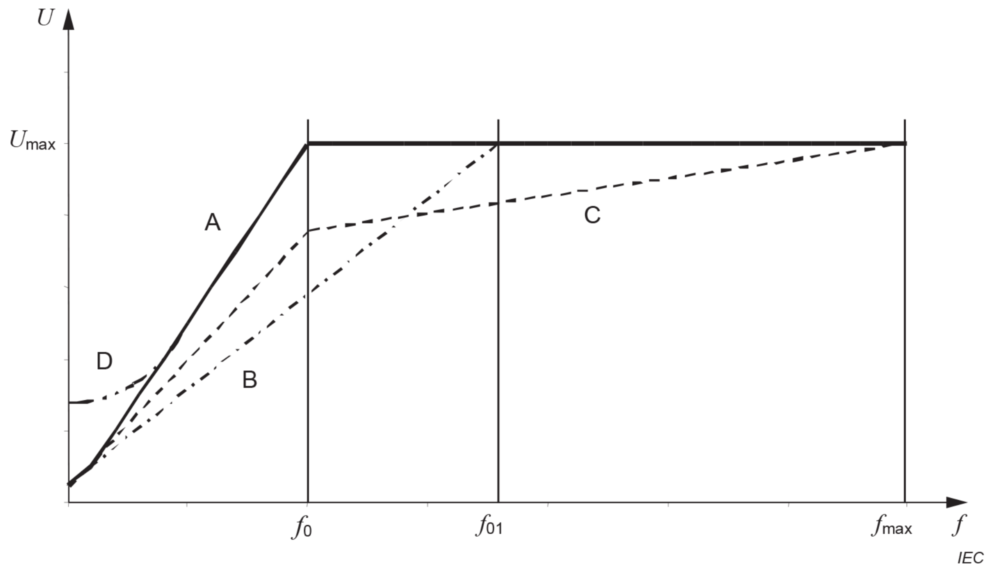
4.3.6 Cooling arrangement

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 ≥ 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 converter*s*)

5.1 General

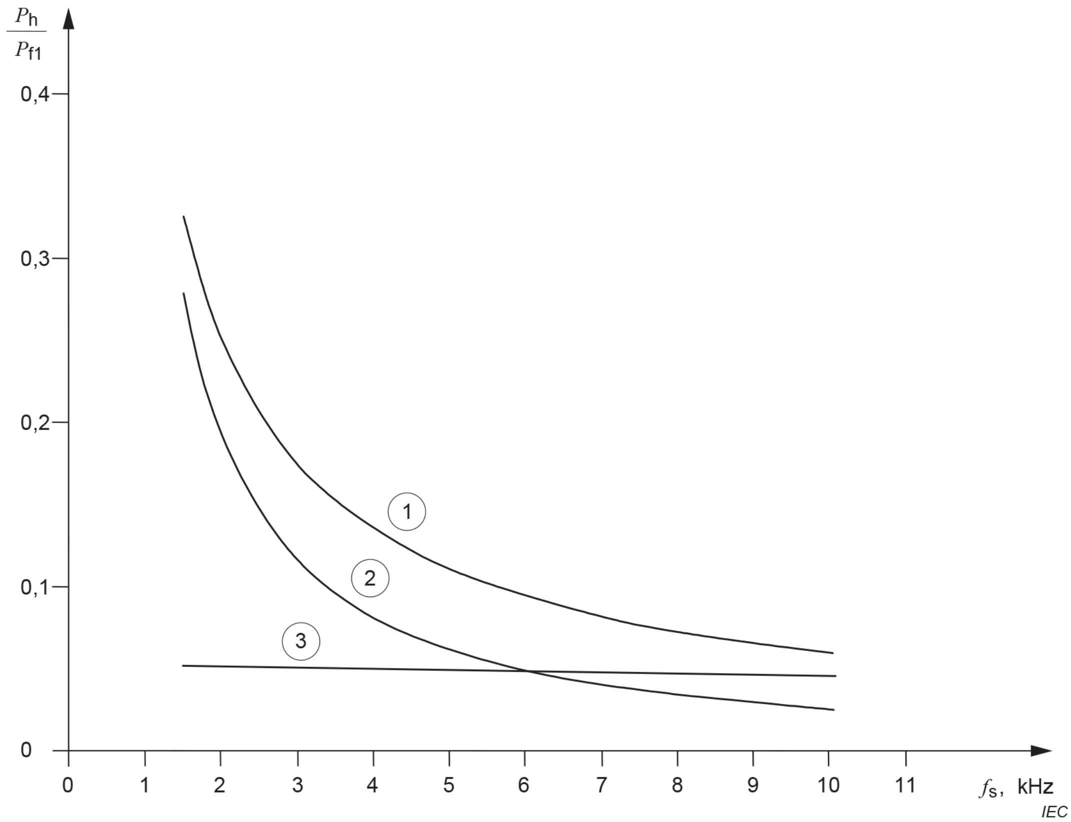
In the case of voltage source converter*s*, a knowledge of the electrical machine equivalent circuit is normally not important for the design of the commutating circuit, but the harmonic impedances of the electrical machine greatly influence the losses caused by harmonics. Voltage source converter*s* 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 converter*s* 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 converter*s* 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 converter*s*, 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).

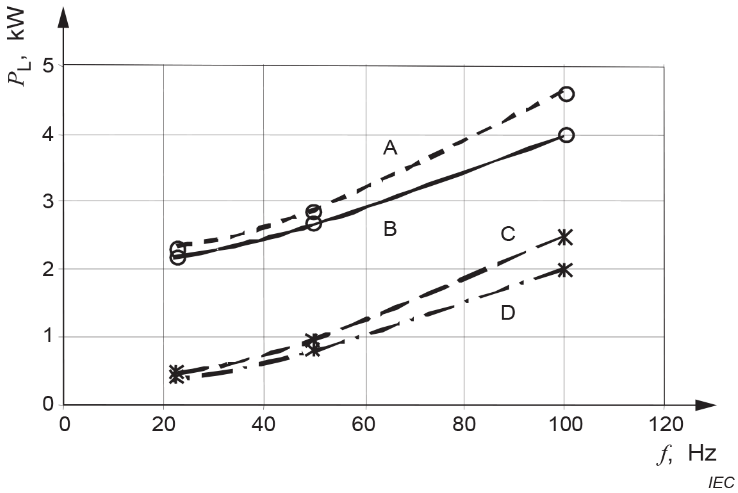
The additional losses due to converter supply can be minimized by various design measures, **either internal or external to the motor,** for example:

- 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.

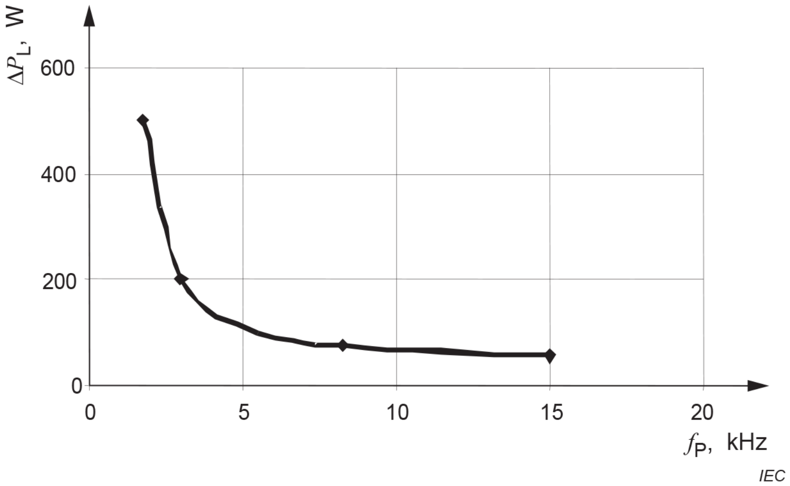


Figure 6 – Additional losses ΔP_L of an electrical machine (same electrical machine as Figure 5) due to converter supply, as a function of pulse frequency f_p, at 50 Hz rotational frequency

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

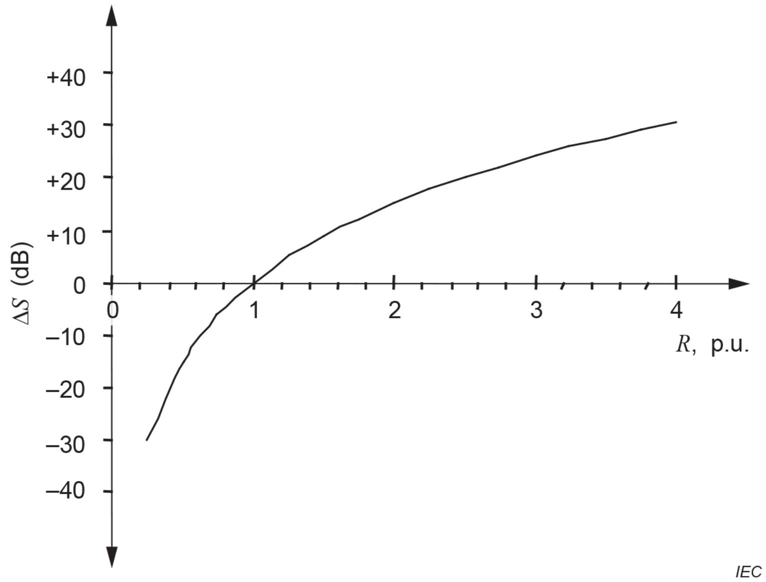
The fundamental frequencies of potential noise emission from a rolling element bearing will vary directly with the rotational speed. If the bearing is ”quiet” at the corner point speed, it is unlikely for the noise level to change significantly when the speed is reduced. However, when the speed is increased 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(dB) will decrease per the following formula $\Delta S(\text{dB}) = 50.\log_{10}(R)$ 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).



Key

ΔS Change in sound pressure

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

R Fan speed p.u.

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

6.1.3 Magnetically excited noise

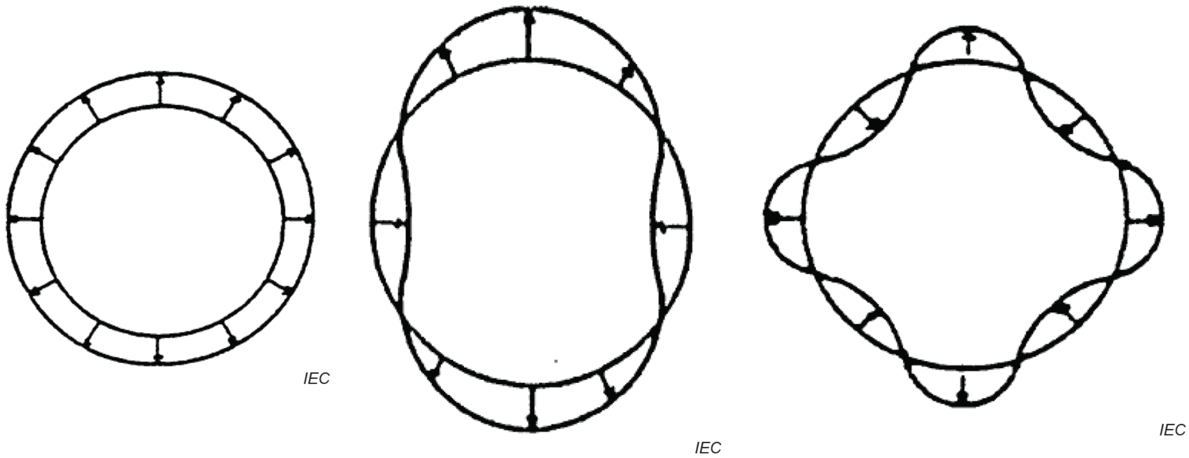
Magnetic noise is essentially caused by waves of tensile stress acting in the radial direction on the stator core at the air gap. These so-called Maxwell forces are excited by the interaction of the various magnetic fields in the air-gap. The tensile stress is characterized by its amplitude, frequency 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.



r = 0 r = 2 r = 4

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).

6.1.4 Sound power level determination and limits

6.1.4.1 Methods of measurement

Sound power levels should be determined in accordance with IEC 60034-9.

6.1.4.2 Test conditions

If practical the electrical machine should be rigidly mounted and, tests should be made with the electrical machine supplied from a converter with the output characteristics that will be used in the application.

Alternatively, and preferably for larger electrical machines, tests may be carried out at no load and rated frequency, using a sinusoidal supply.

6.1.4.3 Sound power level limits

Sound power level limits are specified in IEC 60034-9:2021. Table B.2 of that standard shows, as information, the typical expected increments of the sound power level of converter-fed electrical machines compared with sinusoidal supply.

6.2 Vibration (excluding torsional oscillation)

6.2.1 General

The level of vibration produced by a converter-fed electrical machine will be influenced by the following factors:

- the electromagnetic design of the electrical machine;
- the electrical machine structure, particularly the frame assembly;
- the electrical machine mounting;
- shaft stiffness;
- the rigidity of the coupling between the electrical machine shaft and the driven equipment;
- the output waveform of the converter.

Provided that the converter has suitable output characteristics and also that due attention is paid to the mechanical features of the electrical machine and its mounting, similar vibration levels to that produced by an electrical machine operating on a sinusoidal supply will be obtained. Thus, for electrical machines supplied from PWM voltage source converters, there is no need to establish vibration levels that are different from the figures for sinusoidal supplied electrical machines given in IEC 60034-14.

IEC 60034-14 gives test vibration limits for electrical machines when they are either freely suspended or rigidly mounted. The measured test figures give the vibration level produced by an uncoupled electrical machine under specific mounting conditions and as such are an indication of the quality of the electrical machine. When an electrical machine is mounted in an apparatus or at a site coupled to driven equipment, it is expected that the vibration level will be different.

For an electrical machine coupled to a driven equipment there are many natural resonances and if the application requires the electrical machine to operate over a wide speed range it can be extremely difficult to avoid all of them. If problems are experienced, it is sometimes possible to program the controller so that the frequency bands that are exciting the mechanical resonances are “skipped” (see 4.3.8).

It will be appreciated that as many of the factors influencing the level of vibration are due to the total system, it is not possible to address all vibration problems by considering the design of the electrical machine on its own.

6.2.2 Vibration level determination and limits

6.2.2.1 Method of measurement

Vibration levels should be determined in accordance with IEC 60034-14 (see 6.2.2.2).

6.2.2.2 Test conditions

If practical the electrical machine should be rigidly mounted and, tests should be made with the electrical machine supplied from a converter with the output characteristics that will be used in the application.

Alternatively, by agreement between manufacturer and customer, tests may be carried out at no load and rated frequency, using a sinusoidal supply.

NOTE 1 This recommendation can significantly increase the test time and is not necessary per IEC 60034-14.

NOTE 2 For *in situ* measurements, refer to ISO 10816-3.

6.2.2.3 Vibration level limits

When testing under the conditions specified in 6.2.2.2, it is recommended that the vibration magnitude measured on the bearing housings should not exceed the vibration level Grade A, given in IEC 60034-14.

6.3 Torsional oscillation

The asynchronous (time-constant) torques generated by harmonics have little effect on the operation of the drive. However, this does not apply to the oscillating torques which are generated in the shaft of electrical machines supplied from converters. The magnitude of the torque ripple and its frequency are such that they can produce torque vibrations in the complete connected mechanical system which should be carefully checked in order to avoid damaging mechanical resonances.

In drives with pulse-controlled converters, the frequencies of the dominant oscillating torques are determined by the switching frequency while their amplitudes depend on the pulse width. Thus, the oscillating torque amplitudes may be as high as 15 %, of the rated torque provided that the switching frequency exceeds 10 times the corner point frequency, which is usually the case. With higher switching frequencies (in the order of $21 \times f_1$) the oscillating torques of frequencies $6 \times f_1$ and $12 \times f_1$ are practically negligible, provided a suitable pulse pattern is applied (e.g. modulation with a sinusoidal reference wave or space-phasor modulation). Additionally, oscillating torques of twice the switching frequency are generated. These, however, do not exert detrimental effects on the drive system since their frequency is far above the critical mechanical frequencies.

A DC component, or a negative-sequence component produced by asymmetries of the converter output voltage will generate a torque component of 1- or 2-times fundamental supply frequency and should therefore be carefully prevented. It should be borne in mind that, for DC, only the resistance, and, for negative sequence, a short-circuit impedance, are effective, and therefore small asymmetrical voltages will produce rather high asymmetrical currents and thus oscillating torques, especially when meeting a resonance frequency of the shaft train. Oscillating torques will lead to damage due to clearances in gear sets, couplings or some shaft connections if the torque transmitting surface is able to disconnect and afterwards to "hammer" back.

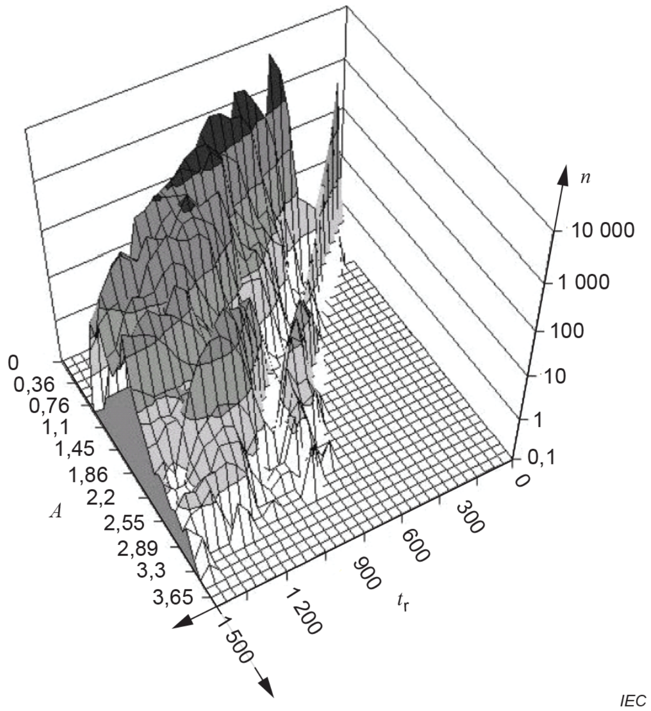
7 Electrical machine insulation electrical stresses

7.1 General

The insulation system of the electrical machine is subjected to higher dielectric stress when converter-fed than in the case of a pure AC sinusoidal source.

7.2 Causes

A voltage source converter generates rectangular pulses of fixed amplitude voltage that have varying width and frequency. The amplitude voltage of the pulses at the output of the converter is generally determined by DC bus voltage (1 p.u.) but the superposition of common-mode and differential mode transient effects throughout the whole topologies of power supply system, converter system plus the auxiliaries like earthing conditions, cabling and filtering have to be clearly analysed and taken into account (see IEC TS 61800-8). Modern low voltage converter output voltage rise-times may be in the 20 ns to 400 ns range. They are kept as short as possible to minimize switching losses in the output semiconductors. These converter*s* can generate repetitive voltage overshoots at the terminals of an electrical machine connected by a cable, which can reduce the life of an electrical machine insulation system if they exceed its repetitive voltage strength. Figure 9 shows a plot of the surge count at the terminals of an electrical machine fed from a converter, measured over a period of time under various operating conditions. As can be seen, there is not a simple relationship between the surge count and the rise-time and magnitude. However, the risk of insulation damage (due to partial discharge, see 7.3 and 7.6) is more severe with surges of fast rise-time and high voltage, which indicates that surges in the upper right-hand portion of this diagram, when viewed from the t_r scale direction are more significant.



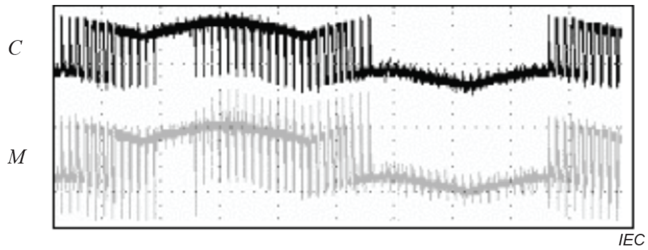
Key

A Surge magnitude (p.u.) t_r Rise-time (ns) *n* Surge count (per second)

Figure 9 – Typical surges at the terminals of an electrical machine fed from a PWM converter

Depending on the rise-time of the voltage pulse at the converter output, and on the cable length and electrical machine impedance, the pulses generate voltage overshoots at the electrical machine terminals (up to 2 p.u. phase-to-phase and phase-to-ground for each polarity). These voltage overshoots are created by reflected waves at the interface between cable and electrical machine terminals due to impedance mismatch, and depend on the converter output, the cable length between the converter and the electrical machine and electrical machine terminal impedance. This phenomenon is fully explained by transmission-line and travelling wave theory, using the harmonic content of the output voltage. As the rise-time decreases, so the harmonic frequencies present in the voltage waveform will increase. Typical voltage surges measured at a converter output and at the electrical machine terminals are given in Figure 10 with an enlarged view of one surge shown in Figure 11. For support of a comprehensive analysis consult IEC TS 61800-8.

It is recommended that the system integrator of converter and electrical machine should measure the phase-to-ground and phase-to-phase voltage at the electrical machine terminals after system installation in order to confirm the expectation, because the actual magnitude and rise-time are complicated as shown in Figure 9. If the actual surge voltage is more severe than the expectation, the system integrator should take countermeasures following 7.5 in order to avoid unexpected system faults in service.

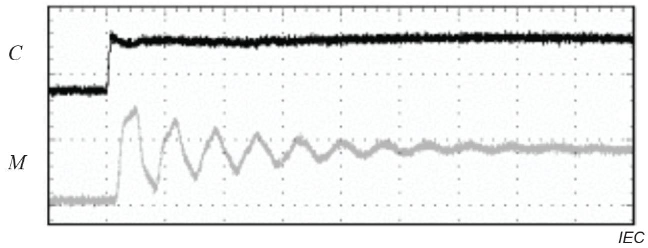


Key

C Phase voltage at converter

M Phase voltage at electrical machine

Figure 10 – Typical voltage surges on one phase at the converter and at the electrical machine terminals (2 ms/division)



Key

C Phase voltage at converter

M Phase voltage at electrical machine

Figure 11 – Individual short rise-time surge from Figure 10 (1 µs/division)

Experience indicates that as the cable length increases, the pulse overshoot generally may increase to a maximum then may decline. Meanwhile, the rise-time at the electrical machine terminals increases. Voltage overshoots might be decreased in the case of installations using converter*s* installed close to associated electrical machines, where the cable length between converter and electrical machine is short.

7.3 Winding electrical stress

The dielectric stress of the winding insulation is determined by the peak to peak voltage and the rise-time (for definition, see Figure 12) of the impulse at the electrical machine terminals, and on the frequency of the impulses produced by the converter.

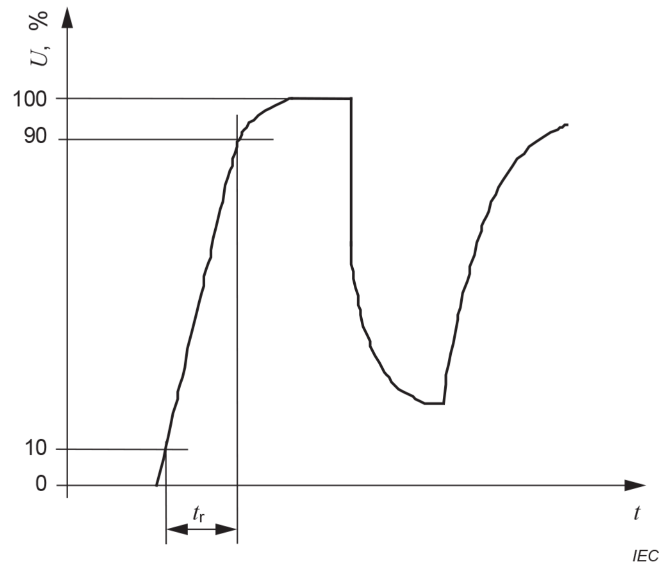


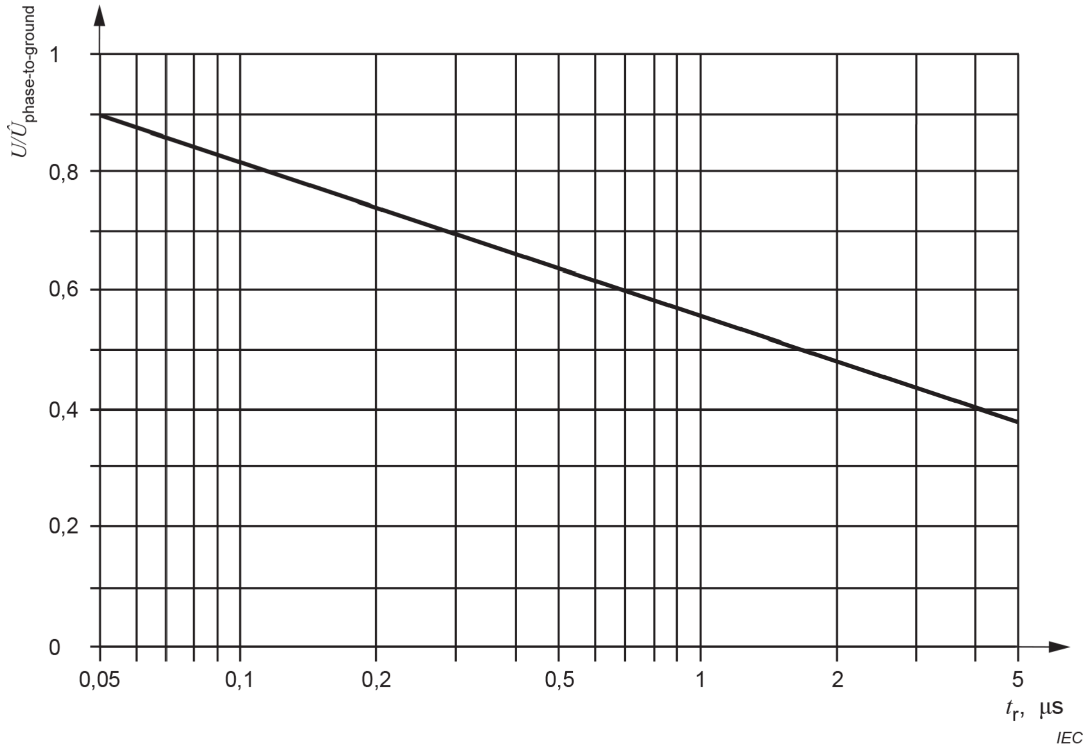
Figure 12 – Definition of the rise-time t_r of the voltage pulse at the electrical machine terminals

One part of the stress is determined by the level of voltage applied to the main insulation (phase-to-phase or phase-to-ground) of the winding coils. The other is limited by the inter-turn insulation and determined by the rise-time of the impulses. Short rise-time impulses result in the voltage being unevenly distributed throughout the coils, with high levels of stress present between turns at the line end coil(s) of the individual phase winding.

Figure 13 shows the worst-case distribution of the voltage across possibly adjacent first and last turns of a random-wound winding as a function of the rise-time.

If not known better, this can be considered as the expected worst-case voltage stressing the turn-turn-insulation of the electrical machine.

As illustrated, the shorter the rise-time, the more voltage appears across the first turn of the coil.



Key

$U/\hat{U}_{\text{phase-to-ground}}$ fraction of jump phase-to-ground voltage

t_r rise-time

Figure 13 – First turn voltage as a function of the rise-time

Short rise-time impulses at electrical machine terminals also cause high turn-to-turn voltages in the first coil(s) of each winding phase and can be followed by early dielectric breakdown turn-to-turn. This can be due to inadequate dielectric strength of the enamel coating, inadequate resin fill. However, field experience has shown, that in most cases no dielectric breakdown occurs, because the probability of critical turns to be located close to each other is rather low when the recommended IVIC are met.

7.4 Limits and responsibility

7.4.1 Electrical machines design for low voltage (≤ 1 000 V)

The insulation system of electrical machines rated at less than 1 000 V specifically designed for supply from voltage source converters may be qualified according to 60034-18-41 (without Partial Discharge Type I) or 60034-18-42 (with Partial Discharge Type II), possibly indicating this in the documentation and on the name plate of the electrical machine. It is the responsibility of the electrical machine manufacturer to document on the nameplate or provided machine documentation the ability of the electrical machine winding insulation. Assigning an IVIC will affect the withstand voltage test in IEC 60034-1.

For general purpose PDS applications it is recommended that the electrical machine should follow the impulse voltage insulation class C/B, Table 4. Electrical machine manufacturer should ensure that the electrical machine complies with these levels, i.e. the values in Table 4.

Higher and lower values as well as different combinations of P-P, P-G, T-T Classes for specific applications are given in IEC 60034-18-41, in order to adapt electrical machine insulation abilities to system requirements economically and reliably.

Ensuring that no significant service lifetime reduction of the electrical machine insulation occurs, the actual stress due to converter operation should be lower than the Impulse voltage insulation class (IVIC) for Type I Insulations according to IEC 60034-18-41 and the voltages per Type II Insulations according to IEC 60034-18-42.

It should be known that dependent on the PDS topology significantly higher voltages could occur. The actual voltage stress to be expected can be determined according to IEC TS 61800-8, taking into account possible voltage reflection depending on the topology and operating mode of the converter, cable type and length, earthing, etc. Relevant parameters for insulation stress are: transient peak to peak voltage values, rise-time, repetition rate, etc.

The system integrator is responsible for determining and specifying the voltage stress level at the electrical machine terminals (see Annex C for an example of the calculation of these voltage stress levels).

In case the actual or expected levels at the electrical machine terminals are higher than those given in the impulse insulation class defined in Table 4 either the PDS topology or the electrical machine insulation shall be adapted. The maximum levels defined in Table 4 covers a sufficient number of typical applications, but it is possible that levels exceed this and the capability of the motor insulation system. It is the responsibility of the system integrator to make system changes or to communicate the special requirements to the electrical machine or converter manufacturer. Methods of insulation stress reduction are given in 7.5.

Table 4 – Operating voltage at the terminals in units of U_N where the electrical machines may operate reliably without special agreements between manufacturers and system integrators

Impulse voltage insulation class	Allowable peak/peak operating voltages in units of U_N	
	Phase/phase C	Phase/ground B
IVIC C/B	5,9	3,1

NOTE Special agreements between manufacturers and system integrators might be subject to a dedicated installation.

7.4.2 Electrical machines designed for medium and high voltage (> 1 000 V)

The insulation system of electrical machines rated at greater than 1 000 V specifically designed for supply from voltage source converters may be qualified according to IEC 60034-18-42 (with Partial Discharge Type II), possibly indicating this in the documentation and on the name plate of the electrical machine. It is the responsibility of the electrical machine manufacturer to specify the ability of the electrical machine winding insulation. Assigning an IVIC may affect the withstand voltage test in IEC 60034-1. Since drive topologies will vary greatly, and these larger motors are mostly custom designed as needed, assigning default IVIC levels is not practical. The end user or system integrator shall work with the converter and motor manufacturer to ensure compatibility. If the drive topology and system are known, IEC TS 61800-8 can be an indication of the peak voltage seen at the at the motor terminals and therefore the motor’s needed IVIC.

7.5 Methods of reduction of voltage stress

There are several possible solutions for reducing the surge severity in a given situation. These can be judged when viewing the complete PDS. Most of the influencing aspects can be calculated by following IEC TS 61800-8. Annex C gives an example of how simple it is to use IEC TS 61800-8.

7.6 Insulation stress limitation

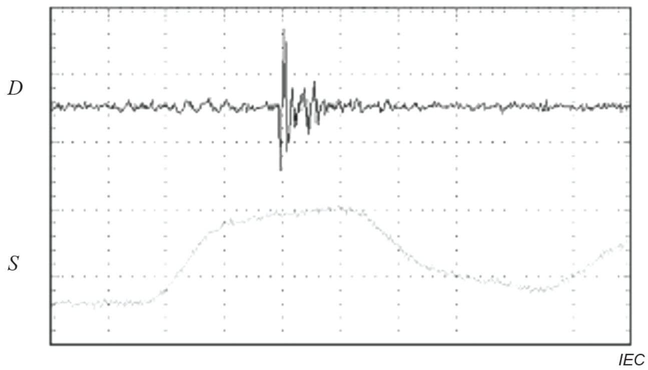
The upper limited level at which this over-voltage stress becomes harmful is the PDIV (the voltage at which partial discharges begin to occur) or, in the air, the Corona Inception Voltage (CIV). Partial discharges may cause degradation of the insulation system through both chemical and mechanical erosion. The rate of insulation degradation depends on the energy and frequency of occurrence of the partial discharges.

PDIV and CIV in an electrical machine are influenced by:

- winding type: random or form-wound;
- design: phase separation and ground wall material;
- varnish type and impregnation technology;
- wire size: larger diameter wire has a higher PDIV;
- wire insulation type;
- enamel thickness: thicker enamel coating of wire increases PDIV;
- operating temperature: when the winding temperature increases, PDIV decreases (typically by 30 % from 25 °C to 155 °C); this is true only partially and in general not for form wound electrical machine windings;
- environment atmosphere (composition and pressure);
- condition of the insulation (contamination by dirt or humidity, etc.).

Figure 14 shows a partial discharge pulse that has resulted from a surge on one phase of a converter-fed electrical machine.

NOTE The discharge occurs at the rising edge of a converter generated voltage surge, as the voltage stress across a void in the insulation reaches its breakdown strength.



Key

S Voltage surge at electrical machine terminals

D Discharge pulse

Figure 14 – Discharge pulse occurring as a result of converter generated voltage surge at electrical machine terminals (100 ns/division)

8 Bearing currents

8.1 Sources of bearing currents in converter-fed electrical motors

8.1.1 General

Several situations can cause bearing currents. Bearings within electric motors as well as the driven load could be affected. The resulting material alternations at the raceways of the bearings in the form of corrugated patterns lead to an early and unplanned shutdown of the drive system. The classification of the different bearing current types is shown in Figure 15.

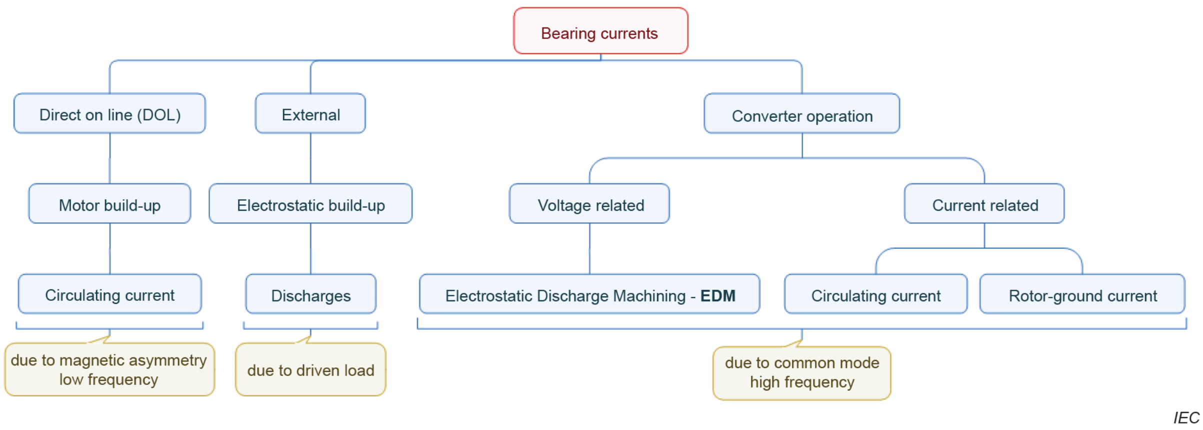


Figure 15 – Classification of bearing currents

NOTE Also auxiliary devices such as encoders or tachometers as per 9.1.4.4 which are connected to the electrical motor can be affected by bearing currents.

8.1.2 Circulating currents due to magnetic asymmetry

Asymmetry in the magnetic circuit of an electrical motor creates a situation that causes low frequency bearing currents. This is more common in electrical motors greater than 400 kW but can exist in small electrical motors with magnetic asymmetries, as well, such as those with a segmented construction. An asymmetric magnetic circuit results in a circumferential a.c. flux (ring flux) in the yoke. This induces an AC voltage in the conductive loop comprising the electrical motor shaft, the bearings, the end brackets, and the outer frame of the electrical motor. If the induced voltage is sufficient to break down the insulation provided by the lubricant, current will flow through the loop, including both bearings. This kind of bearing currents mainly appears in direct on-line operating motors systems

8.1.3 Electrostatic build-up

The voltage can also be caused by an electrostatic build up on the shaft due to the driven load such as an ionized filter fan.

8.1.4 High-frequency effects in converter operation

The converter transforms the input voltage from the supply, which is, as a first approximation, constant in amplitude and frequency, into a variable voltage in frequency and amplitude. For that purpose, a rectifier unit is feeding a DC voltage link, in which DC link capacitors act as voltage smoothers and energy storage. The subsequent inverter transforms the DC link voltage with the procedure of pulse-width modulation into a variable AC voltage. In this way, the connected electrical motor can be controlled in terms of speed and torque.

Regarding to the characteristics of inverter-related bearing currents, the high-frequency properties of the earthing system are of particular importance. Due to the use of fast switching semiconductors, which are operated at high switching frequencies, the inverter shall be assigned the role of an interference source within a Power Drive System – in sense of EMC. The interference sinks are the subsequent electro-mechanical components such as the electric motor, gear unit and driven machine, via which the conducted, asymmetrical interference currents flow. These cause additional, high-frequency voltage drops at the components of the drive system. Due to the respective parasitic conditions, each component of the system has a corresponding impedance to earth at which additional voltages drop. In Figure 16 these are marked u_{G0} to u_{G4}.

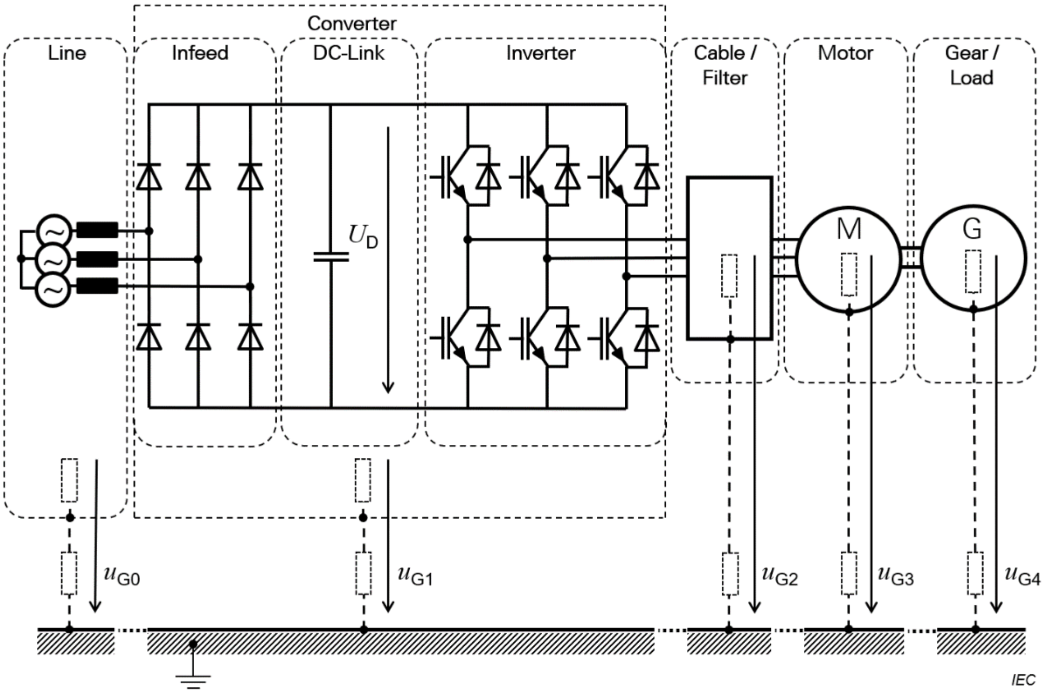


Figure 16 – Parasitic impedances to earth of drive system components

Based on the typical output voltage waveform of VSI converters, the mechanisms can be divided into three types of bearing currents: EDM, circulating and rotor ground currents. Due to the underlying mechanisms, these can be divided into two main groups: the current related and the voltage related bearing currents. Within the former group the bearing currents are caused by the high-frequency components of the common-mode current (circulating and rotor ground currents) while for the latter group these are generated due to the inherent common-mode voltage (EDM currents). The classification of the aforementioned bearing current types is depicted in Figure 15.

8.2 Generation of high-frequency bearing currents

8.2.1 Common mode voltage

A significant side effect in the operation of voltage source inverters (VSI) is the inherent occurrence of a common mode voltage. Since only discrete voltages and switching states are available in a VSI, the sum of the generated phase voltages (u_{RG}, u_{SG}, u_{TG}) is usually non-zero – which is different to classical three-phase AC system. In addition to that, the respective modulation methods inevitably require the switching of zero vectors to generate the desired output voltage. These are states of operation, where the positive or the negative DC link voltage is connected to the three motor terminals. The resulting common mode voltage represents the input voltage of the described parasitic network. This means, it is – as a source – also an influencing factor for the undesired, parasitic bearing current. The common mode voltage is equal to one third of the sum of the three voltages phase-to-ground. In Figure 17 – on the right, the typical common mode voltage waveform u_{CM} of a two-level inverter with a diode front end as three phase rectifier is exemplified as well as the resulting common mode currents. Steps of $\pm U_D/6$ and $\pm U_D/2$ with the corresponding fast voltage changes du/dt can occur. At each change, the resulting common mode current pulse i_{CM} is clearly visible.

The manner and degree to which this CMV is expressed at the terminals is dependent on the specific Converter topology converter infeed, grounding, etc. The resultant electrical bearing stress will depend on a number of system design factors including ASD carrier frequency, motor geometry, cable type and drive train interaction.

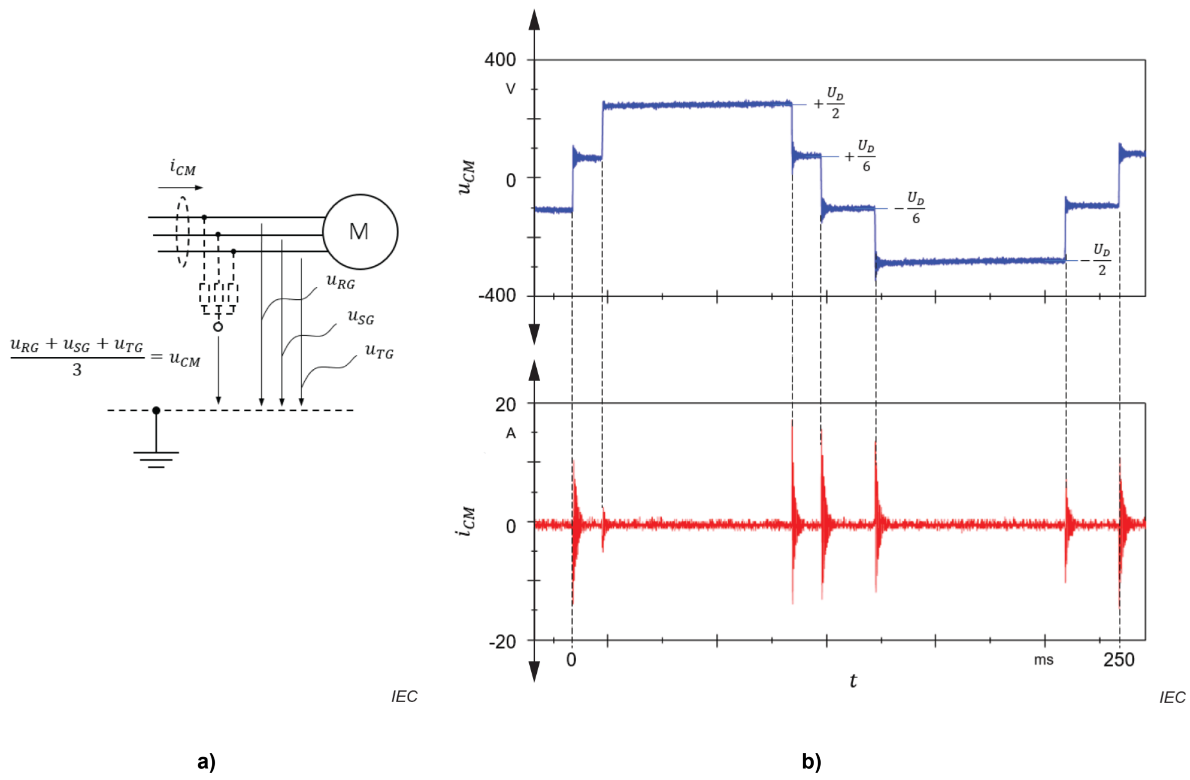


Figure 17 – Common mode voltage a) determination b) waveform example

8.2.2 Motor HF equivalent circuit and the resulting bearing current types

Practically, the common mode voltage is the input variable for the parasitic network which is established by the subsequent drive system. For the high-frequency equivalent circuit of the motor the components of this network shall be explicitly considered as interface areas, air gaps and insulation inside the drive system. The HF equivalent circuit diagram of the motor is depicted in Figure 18. The applied common mode voltage u_{CM} generates the current component i_{CM}, to flow mainly through the parasitic capacity component C_{WS}. This capacity component is formed between the winding system of a motor and its stator. Other capacities are present between winding and rotor (C_{WR}), between rotor and stator (C_{RS}) and inside the rolling bearings (C_B). While the first three portions are determined solely by the geometric dimensions, the latter is heavily dependent on the operating conditions. Speed, temperature, bearing load and the excitation of vibrations have a very strong impact on the bearing capacity.

The current flow into the bearings can change rapidly, depending on the condition of the bearing. For instance, the presence of capacitance in the bearings is only sustained for as long as the anti-friction bearings are covered in lubricant and are non-conducting. This capacitance can be short-circuited if the bearing voltage exceeds the threshold of the breakover value or if the bearing lubricant film is depleted and makes contact with both bearing races. At very low speed, the bearings may also have metallic contact due to the lack of insulating lubricant film.

The main focus is on the alterations in roller bearings. Slide bearings rarely show any irregularities caused by current passage, firstly due to a more distinct separation of the sliding partners (lubrication film thickness is 40 up to 50 times bigger compared to roller bearings) and secondly due to the non-existent rolling mechanism. As a consequence of this sleeve bearings usually have little to no abnormalities that could be traced back to an electrical stress on the bearings.

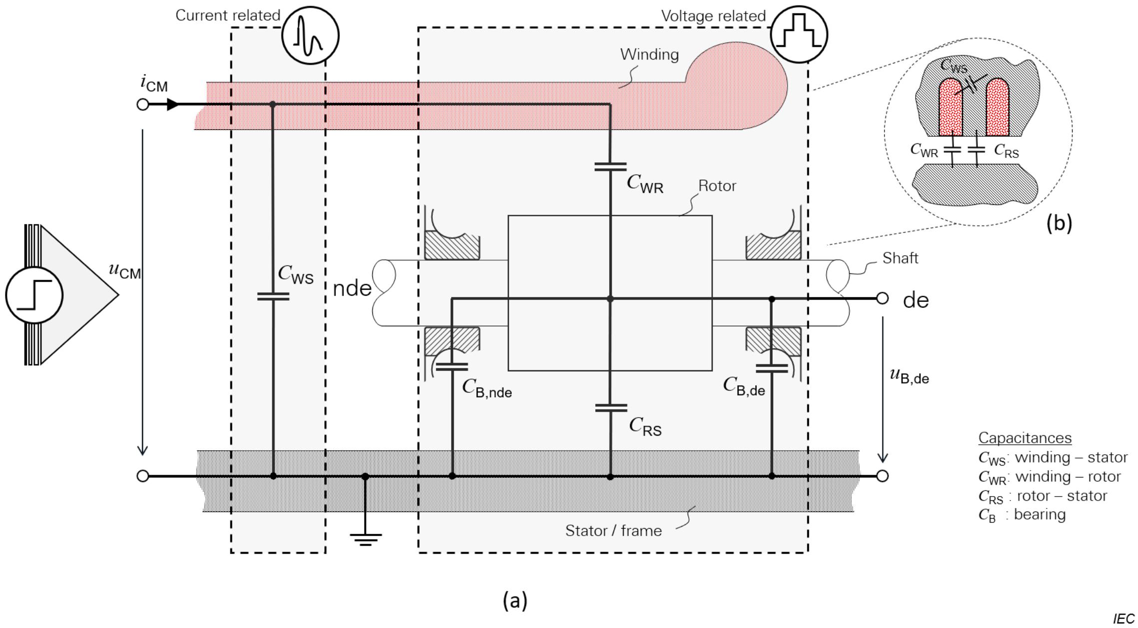


Figure 18 – HF equivalent circuit diagram (a) of a motor (b) geometrical representation of capacitances

A distinction is made between three types of bearing currents (Figure 15): high-frequency circular currents inside the motor as well as high-frequency currents from rotor to ground (current related bearing currents) and the EDM currents with flash-overs in the lubrication film of the bearing (voltage related bearing currents). For every rapid change of the common mode voltage a common mode current peak occurs (Figure 17). Only in this instant a current related bearing current may appear. The characteristically waveform for such a bearing current event can be described with two magnitudes: the peak value of the current and the basic frequency of the following damping oscillation which is in the range of 200 kHz to 300 kHz. Additionally, the number of peak events per time unit which is directly connected to the common mode voltage slope defines the appearance frequency of this current related bearing currents.

On the other hand, the voltage related bearing currents are strongly related to the voltage drop across the lubrication gap of the bearing which is a portion of the common mode voltage as depicted in the motor HF equivalent circuit (Figure 18). This kind of bearing current can be described also by a peak value and the basic frequency of the following damping oscillation which is in the range of 1 MHz to 5 MHz. In this case the number of peak events per time unit is directly connected to the isolation ability of the lubrication film inside the bearing.

A graphical representation of the different high harmonic bearing current types highlighting the involved physical components of the drive unit is shown in Figure 19. These types of bearing currents are principally shown in a schematic drive system in Figure 19. These are explained in detail in the following subclauses.

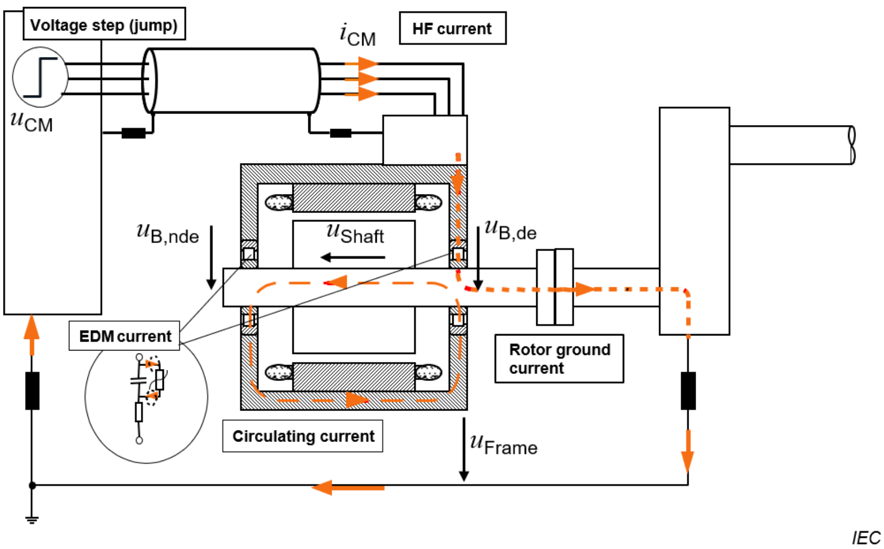


Figure 19 – Graphical representation of the different high frequency bearing current types in the drive unit highlighting the involved physical components

8.2.3 Circulating current

The circular currents depicted in the left part of the equivalent circuit diagram in Figure 20 has a crucial influence – in form of the parasitic capacity between winding and stator lamination C_{WS}. The high-frequency common mode current, which is flowing off via the slot insulation, induces a circular magnetic flux, which encircles the shaft of the motor. The voltage induced by that flux into the shaft of the motor causes a high-frequency circular current, which closes over: laminated core – bearing shield – motor bearing – shaft. This differs from the classical circular bearing current which leads to a circular current with motor fundamental frequency due to magnetic unbalances. The circular current caused by converter operation features has a significantly higher frequency. The circumstances are schematically shown in Figure 20, on the left. On the right-hand side, the current time plots, measured at both motor bearings are indicated. Both current courses show a phase displacement of 180° at identical amplitude and thus they represent a circular current. This circulating current typically causes damage to the bearings with typical peak values of 3 A to 20 A, depending on the size of the electrical motor, the rate of rise of the voltage at the electrical motor terminals and the DC link voltage level.

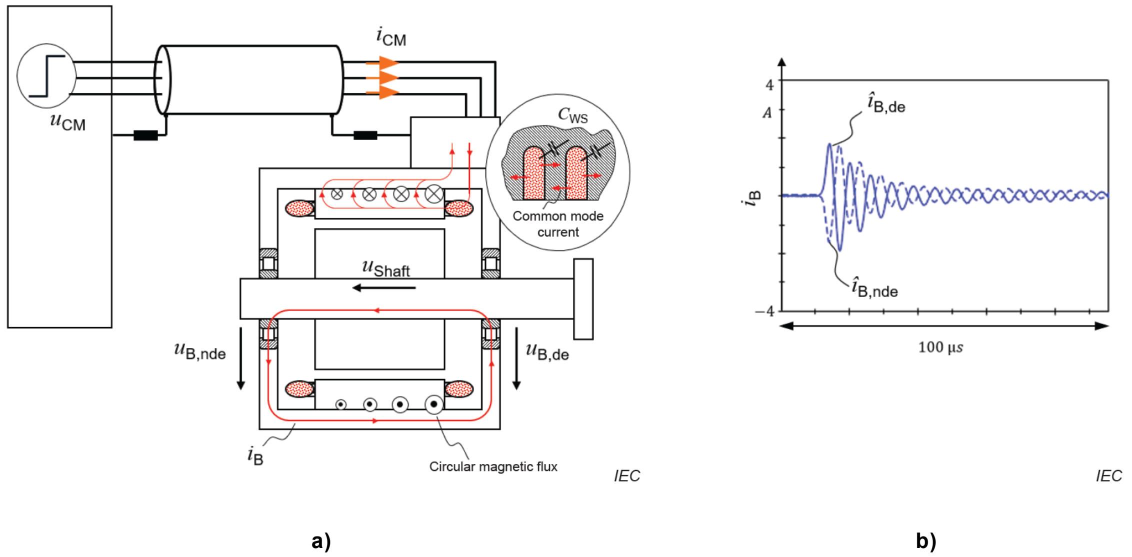


Figure 20 – Principle of circulating currents formation

8.2.4 Rotor ground current

The current flowing from the winding through the capacity C_{WS} – illustrated in Figure 18 – to the stator core lamination is routed back via the enclosing grounding system to the source – the DC link of the converter. In case, the grounding conditions at the motor are designed in such a way, that a path of low impedance is leading to the shaft of the motor, currents of considerable amplitude can flow via the connection motor shaft coupling a load. In this way, they can potentially damage electrically passive plant component that are connected to the motor. Thus, the amplitude of the current from rotor to ground is strongly dependent on the quality of the enclosing grounding system. In Figure 21, the possible current paths are illustrated that are originated by the extension of the HF equivalent circuit diagram depicted in Figure 18. Here, the capacities of the motor, the load and the impedances of the enclosing grounding system can be identified.

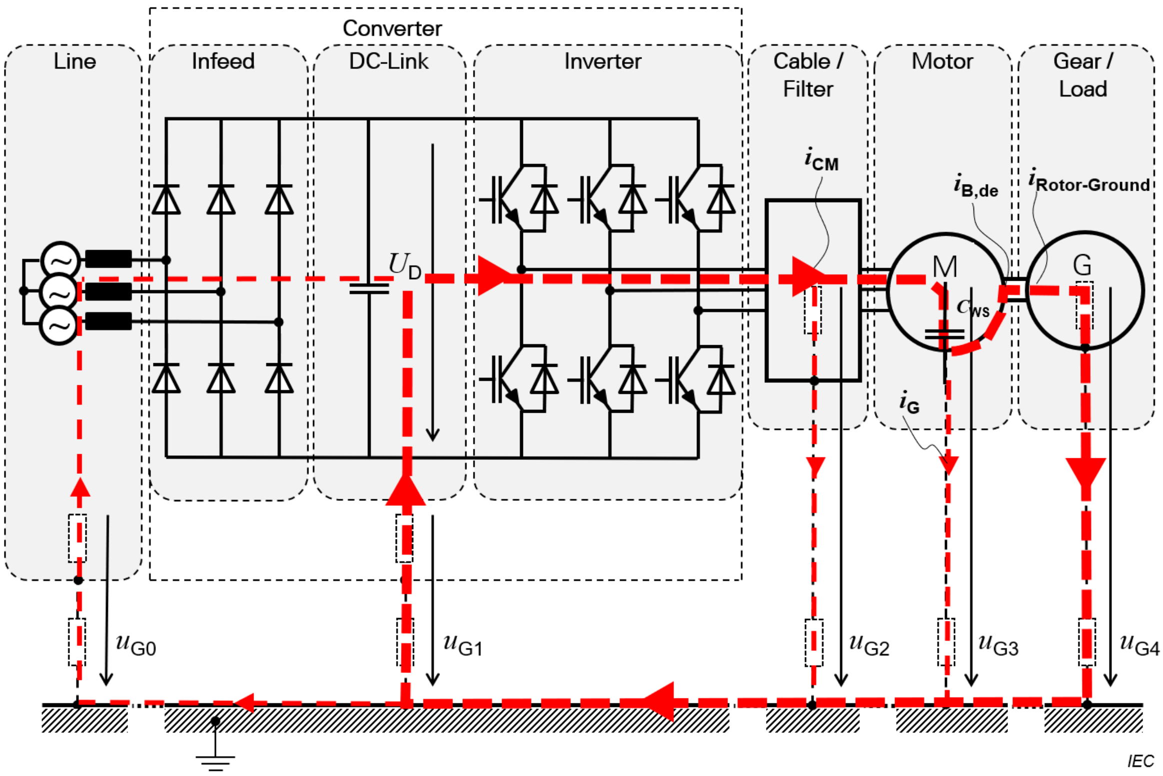


Figure 21 – Rotor ground current principle

The potential difference between the electrical motor frame to ground is a portion of the converter's common-mode voltage. The common-mode current will seek the path of least impedance. If a high amount of impedance is present in the intended paths, like the ground connection of the electrical motor frame, the electrical motor frame voltage will cause some of the common-mode current to be diverted into an unintended path, such as through the building. In practical installations, a number of parallel paths exist. Most have a minor effect on the value of common-mode current or bearing currents, but may be significant in coping with EMC requirements.

However, if the value of this impedance is high enough, voltage drops of over 100 V may occur between the electrical motor frame and the converter frame. If, in such a case, the electrical motor shaft is connected through a metallic coupling to a gear box or other driven machinery that is solidly grounded and near the same potential as the converter frame, then it is possible that part of the converter common-mode current flows via the electrical motor bearings, the shaft and the driven machinery back to the converter.

If the shaft of the machinery has no direct contact to the ground level, current may flow via the gear box or load electrical machine bearings. These bearings may be damaged before the electrical machine bearings.

8.2.5 Electrostatic Discharge Machining (EDM) currents

This type of bearing current is named according to the manufacturing process on the basis of spark erosion, the so-called Electrostatic Discharge Machining. The basis for that is the application of the common mode voltage from the parasitic motor capacities on the lubrication gap of the rolling bearing. The capacities between winding and rotor and between rotor and stator constitute a voltage divider, which generates a potential difference between rotor and stator of the motor, and thus driving a bearing current i_B. The voltage ratio can be described by the Bearing Voltage Ratio (BVR) in the following formula:

$$\frac{u_B}{u_{CM}} = BVR = \frac{C_{WR}}{C_{WR}+C_{RS}+2 \cdot C_B}$$

In case the voltage across the bearing exceeds the breakdown voltage of the lubrication film in the bearing, the resulting arc discharge will melt or vaporize material out of the bearing raceway. In Figure 22, the waveforms of the common mode voltage, the bearing voltage at the DE bearing as well as the resulting bearing current are exemplified. The bearing current can follow the stepped characteristic of the common mode voltage only partially, and a corresponding bearing current is measurable in the case of a voltage breakdown. The amplitude of the EDM bearing currents is depending on the amplitude of the common mode voltage of the converter, on the parasitic motor capacitances and especially on the load- and operating-point-dependent lubrication conditions in the roller bearing of the driving motor. The energy content of the arc discharge which is caused by these EDM currents is compared to the circular currents and rotor-to-ground currents which may be significantly smaller, but it can progressively also lead to the formation of ripples in the bearings.

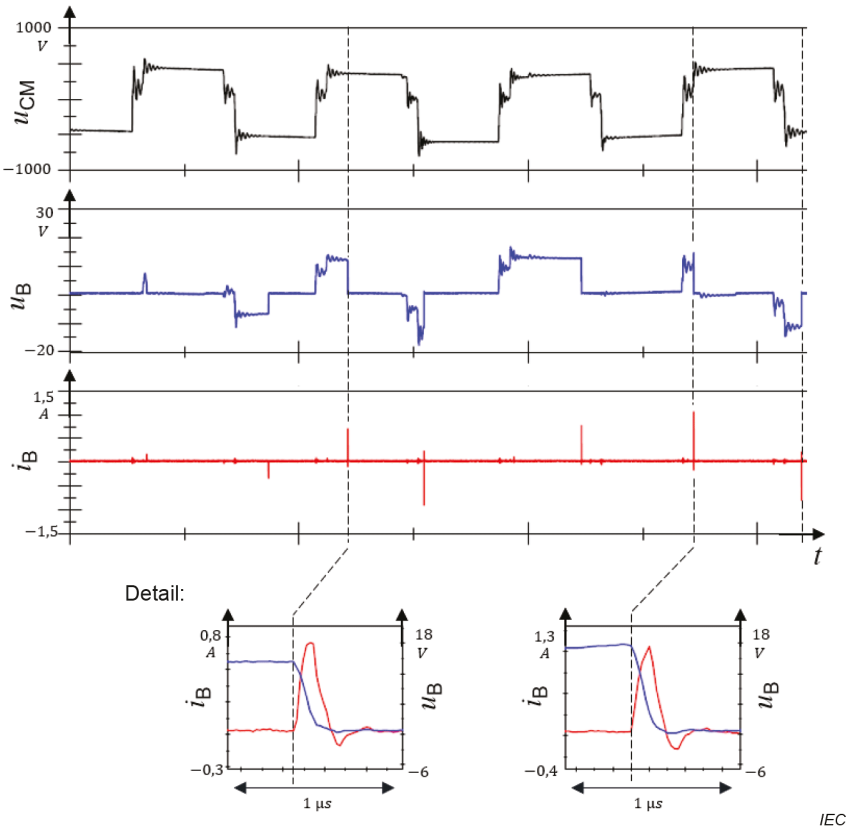


Figure 22 – Example of measured EDM-current pulses for a 400 V and 500 kW induction motor in converter operation

8.3 Consequences of excessive bearing currents

Characteristic damages in roller bearings due to current passage are described in the following. The arc flash, which is developing in the lubrication gap and the subsequent current flow have – among others – the following consequences:

a) The energy, which is unleashed by the arc flash, results in material melt-out or vaporization in the load zone of the roller bearing. Depending on the run time, these changes can propagate over the complete circumference.

b) The lubricant changes its composition, and the lubricity will decrease.

The meltings mentioned in a) predominantly result in the formation of a crater-like formation with material properties that are deteriorated compared to the original condition. The hardened material is much more brittle, the underlying layer is annealed and thus softer than the basic material. These meltings (size approximately 1 µm to 5 µm) consolidate to a porous, spongy-like structure and lead to the typical "matt-frosted" appearance of current-loaded raceway surfaces. In Figure 23b the conditions are depicted macroscopically and microscopically in form of a scanning electron microscope (SEM) exposure. Generally, the frosted raceway has no influence on the lifetime of the bearing. However, the formation of ripples ("washboarding") turns out to be much more problematic, which is characterized by a multitude of heterochromatic, gray lines, crosswise to the raceway (Figure 23c). These lines are formed by a virtually periodic mountain-and-valley structure of the raceway surface. This "washboard" dynamically excites the rolling elements to vibrate, which results in an extremely increased wear of the bearing components. This can result in fatigue fractures and following bearing failure.

As denoted under b), the lubricant changes its consistency and loses lubricity. The basic oil with the correspondent additives is bonded in the so-called soap frame. Due to the high temperatures, these substances are reacting: the soap frame and the basic oil are burning or coking, and the additives often decompose quickly. After all, the lubricant will be discoloured in black and hardened (Figure 23a). This disintegration of the lubricant is a typical effect of damage as a result of current passage. It could decisively influence the lifetime of the lubricated roller bearings without regreasing device.

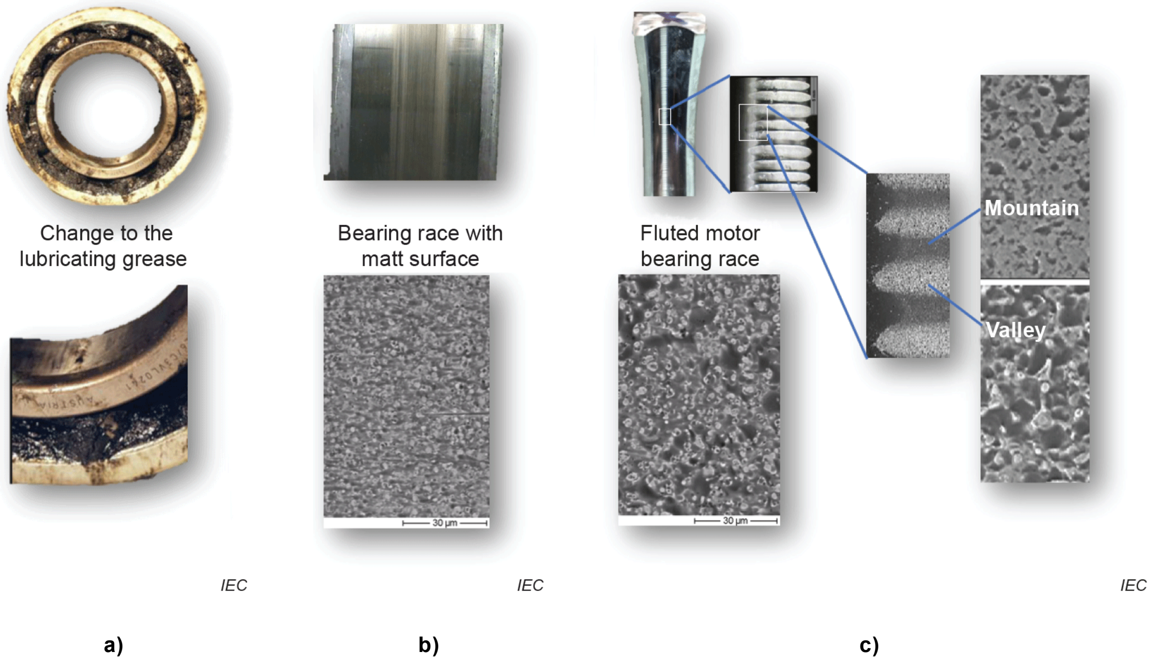
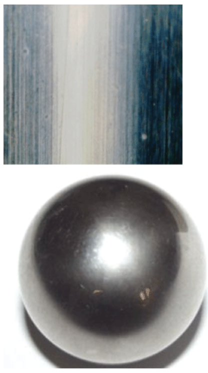
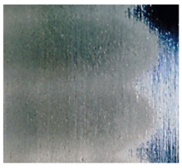


Figure 23 – Photographs of damaged motor bearings

Table 5 shows different shapes of roller bearing damages in various grades. This is based on macroscopic images of the outer raceway, the balls and the lubricants of different roller bearings, which have been operated approximately 50 000 h in motors of different shaft heights. Starting from the initially slight ripple formation (Grade 1), the transition to fatigue failures (Grade 5) is shown in five steps. It should be noticed that Grade 0 corresponds to the gray frosted raceways that have no influence on bearing lifetime. Grade 1 (light corrugation) shows a sequence of a multitude of small melting craters. Here, the frosting is an optical impression which can be attributed to a change in light scattering, induced by the summation of the melt craters. In the case of the damage of Grade 2, the first indications (shades) of an emerging crosswise ripple formation are visible. In this phase, the lubricant already shows the typical black discolorations, which become perceptible with increasing degree of damage. From Grade 3 (medium corrugation) to Grade 4 an increasing crosswise ripple formation (fluting) becomes visible. Likewise, the black coloration of the grease clearly indicates the influence of an electrical bearing load. Finally, Grade 5 (heavy corrugation) corresponds to a bearing that exhibits fatigue failures in the raceways and at the balls in addition to the corrugation. This is adequate to a condition that can occur in the course of the far advanced damage process of ripple formation.

Table 5 – Different grades of roller bearing damages

Corrugation level	Grade	Outer ring	Detail / Ball	Grease	Size / Type
Grey frosted	0	 IEC	 IEC	 IEC	SH 315 6218 C3
Light	1	 IEC	 IEC	 IEC	SH355 6220 C3

Corrugation level	Grade	Outer ring	Detail / Ball	Grease	Size / Type
Light / medium-	2	 IEC	  IEC	 IEC	SH 315 6220 C3
Medium	3	 IEC	  IEC	 IEC	SH 450 6226 C3

Corrugation level	Grade	Outer ring	Detail / Ball	Grease	Size / Type
Medium / heavy-	4	 IEC	 IEC	 IEC	SH 355 6220 C3
Heavy	5	 IEC	 IEC	 IEC	SH 355 6226 C3

8.4 Preventing high-frequency bearing current damage

8.4.1 Basic approaches

There are four basic approaches used to prevent high-frequency bearing currents, which can be used individually or in combination:

- a proper cabling and earthing system;
- modifying the bearing current loops;

- damping the high frequency common-mode current;
- damping the high frequency common-mode voltage.

All these tend to decrease the voltage across the bearing lubricant to values that do not cause high-frequency bearing current pulses at all or dampen the value of the pulses to a level that has no effect on bearing life. For different types of high-frequency bearing currents, different measures need to be taken.

The basis of all high-frequency current solutions is the proper earthing system. Standard equipment earthing practices are mainly designed to provide a sufficiently low impedance connection to protect people and equipment against system frequency faults. A variable speed drive can be effectively grounded for high common-mode current frequencies, if the installation follows the principles of Clause 9.

8.4.2 Other preventive measures

- Use insulated bearing(s).

  NOTE 1 Several kinds of bearing insulation with different thickness and placed at different locations (for example, between shaft and inner bearing race, between outer bearing race and end-bracket, between end-bracket and frame) are in practical use. Anti-friction bearings with a ceramic coating at the outer surface (so-called coated bearings) are customary. Bearings with ceramic rolling elements are also available.

- Besides the improvement of the impedance conditions, the use of additional common mode inductivities (chokes) can reduce the excitation, i.e. the common mode current. The attachment of nanocrystalline iron cores at the output of the inverter is also a preventive measure. For that, the iron cores shall be installed in all three phases (without ground).

  NOTE 2 The optimum number of iron cores depends on the selected type of cable, the cable length and the motor power. The effectiveness of the iron cores is limited to high frequencies, i.e. low-frequency components in the common mode current will result in a magnetic saturation of the iron cores. These low-frequency components can arise, e.g. from unsymmetrical motor cables or single conductor arrangements. Magnetic saturation can result in an almost complete neutralization of the effectiveness in the high-frequency range. With respect to the previously described EDM currents, the iron cores are not effective at all.

- Use a filter that reduces common-mode voltages and/or $\mathrm{d}u/\mathrm{d}t$.
- Use non-conductive couplings for loads or other devices which may be damaged by bearing currents.
- Use brush contact(s) between shaft and electrical motor frame.
- Use lower voltage electrical motor and converter if possible.
- Run the converter at the lowest switching frequency that satisfies audible noise and temperature requirements.
- Avoid simultaneous switching of two inverter phases in opposite polarity. (parallel switching).

Table 6 compares the effectiveness of some of these measures.

Table 6 – Effectiveness of bearing current counter measures

Counter measure	Current type			Additional comments
	Circulating currents (8.2.3)	**Rotor ground currents (8.2.4)**	**EDM currents (8.2.5)**	
1) NDE bearing insulation	Effective	Not effective: Only protects one bearing	Not effective: Does not prevent against the voltage drop across the bearing lubricating film	NDE insulated to avoid need for an insulated coupling
2) NDE bearing with ceramic rolling elements	Effective	Not effective: Only protects one bearing	Not effective: Only protects one bearing	The use of similar bearing types on DE and NDE is recommended
3) NDE and DE bearing insulation	Effective: One insulated bearing is adequate for this current type	Effective	Not effective: Does not prevent against the voltage drop across the bearing lubricating film	Require additional brush contact to prevent rotor grounding by the load
4) NDE and DE bearing with ceramic rolling elements	Effective: One insulated bearing is adequate for this current type	Effective	Effective	Require additional brush contact to prevent rotor grounding by the load
5) NDE and DE bearing insulation + shaft earthing brush DE	Effective	Effective Does not protect bearings in driven load	Effective	Servicing necessary
6) NDE and DE bearing insulation + shaft earthing brush NDE	Effective	Effective Does not protect bearings in driven load	Effective	To prevent circulating bearing currents in the loop of motor and load the use of an insulated coupling is mandatory Servicing necessary
7) NDE and DE bearing insulation + insulated coupling + shaft earthing brush DE or NDE	Effective	Effective	Effective	Most effective (especially for larger electrical motors). Helps to prevent possible damage to driven load. Servicing necessary
8) NDE and DE bearing insulation + **insulated coupling**	Effective	Effective	Not effective: Does not prevent against the voltage drop across the bearing lubricating film	To prevent floating rotor potential the use of a shaft earthing is mandatory (see measure 7)
9) NDE and DE bearing with ceramic rolling elements + **insulated coupling**	Effective	Effective	Effective	To prevent floating rotor potential the use of a shaft earthing is mandatory (see measure 7)

Counter measure	Current type			Additional comments
	Circulating currents (8.2.3)	**Rotor ground currents (8.2.4)**	**EDM currents (8.2.5)**	
10) One brush contact **No bearing insulation**	Not effective: Only protects one bearing. Increase of circulating bearing currents in the non-insulated bearing	Effective: Does not protect bearings in driven load	Effective: Care needed to ensure low brush contact impedance	Critical especially for larger electrical motors Servicing necessary
11) Two brush contacts, DE and NDE **No bearing insulation**	Effective: Care needed to ensure low brush contact impedance Increase of circulating bearing currents.	Effective: Does not protect bearings in driven load	Effective: Care needed to ensure low brush contact impedance	Servicing necessary Increased brush wear due to increased circulating currents
12) Low resistance lubrication and/or carbon-filled bearing seals	Poor	Poor	Effective: Depends on condition of materials	No long term experiences. Lubrication effectiveness reduced
13) Rotor in Faraday cage	Not effective	Not effective	Very effective	Problems from converter generated circulating currents that normally only occur in larger electrical motors
14) Common mode inductivities (chokes)	Effective	Effective Limited effectiveness due to Saturation effects caused by high common-mode current peaks and/or low-frequency components	Not effective	The effectiveness of the iron cores is limited to high frequencies.
15) Common-mode voltage filter	Effective: Reduced HF voltage also decreases LF currents	Effective	Effective	Greatest reduction of common-mode voltage if filter is fitted at converter output
16) Insulated coupling	Not effective	Very effective	Not effective	Also prevents possible damage to driven load
17) Frame to driven load connection	Not effective	Effective	Not effective	Also prevents possible damage to driven load
18) Use of symmetrical, shielded motor cable	Not effective	Very effective	Not effective	Also prevents possible damage to driven load
DE: Drive End. NDE: Non Drive End.				

8.4.3 Other factors and features influencing the bearing currents

- Large physical size or high output power of the electrical motor tends to increase the induced shaft voltage.
- The physical shape of the electrical motor also has an effect on the induced shaft voltage: short and thick shape is generally better than long and thin electrical motor design.
- High pole numbers tend to reduce the induced shaft voltage.
- High stator slot number tends to increase the shaft voltage.
- High break down torque means low stray reactance and higher shaft voltage.
- Short electrical motor cable increases the induced shaft voltage.
- Low running speed and high bearing temperature as well as high bearing load increase the bearing current risk due to thinner lubricant film.
- Roller bearings are more vulnerable than sleeve bearings but have higher endurance than ball bearings due to higher clearances and capacitances.
- An active front end of the converter may increase the bearing voltages considerably depending on the earthing configuration.
- Slip-ring electrical motors supplied by voltage source converter*s* in the rotor circuit require special attention because the bearing voltage ratio (BVR) is much higher (BVR ≈ 1) than in stator-fed electrical motors.

8.5 Additional considerations for electrical motors fed by high voltage source converter*s*

8.5.1 General

All the bearing current statements made before with respect to low-voltage electrical motors supplied by voltage source converter*s* are valid in general for high-voltage electrical motors and converter*s,* but there are also some differences, as shown in the following examples.

- High-voltage electrical motors have usually high output power (from hundreds of kW upwards) and they are rather big in frame size; therefore, they usually have one insulated bearing as standard.
- Thicker slot insulation reduces the winding-core capacitance, reducing also the electrical motor common-mode current and the circulating type bearing current risk.
- On the other hand, the voltage steps of the common-mode voltage are much larger in high-voltage converter*s*, in spite of the higher number of steps, increasing the circulating current risk.
- Due to high voltage at the d.c. bus the common-mode voltage amplitude is high and, therefore, the capacitive discharge bearing current risk is considerable (BVR of high-voltage electrical motors is in the same range as in low-voltage electrical motors).

8.5.2 Bearing protection of cage induction, brushless synchronous and permanent magnet electrical motors

The high-voltage in the converter intermediate circuit and the physical size of the electrical motor emphasize to protect the bearings. Use insulated bearing structure for both bearings or one insulated (NDE) bearing and an effective shaft earthing brush at the DE bearing or an effective common-mode filter at the converter output (see Table 6).

8.5.3 Bearing protection for slip-ring electrical motors and for synchronous electrical motors with brush excitation

As the electrical motor already has slip rings and brushes, an additional effective shaft earthing brushes in both ends will protect the bearings. Alternatively, another applicable method from Table 6 may be selected.

If the voltage source converter is connected into the rotor circuit, high common-mode voltage and BVR are to be expected. Therefore, special attention should be paid to the bearing protection in these circumstances.

8.6 Bearing current protection for electrical motors fed by high-voltage current source converter*s*

Practical experience and tests have shown that current-source converter supply has little impact on shaft voltage and, therefore, no special measures for bearing protection are necessary.

Earthing brushes are recommended only for slip-ring electrical motors supplied by current source converter*s* in the rotor circuit shaft.

9 Installation

9.1 Earthing, bonding and cabling

9.1.1 General

The recommendations in 9.1 give general guidance only on the suitability of conductors for use as PE connections and electrical machine cables, and on reliability and EMC installation issues. For specific installations, local regulations concerning earthing should be followed and agreed with the system integrator, and the converter supplier's instructions concerning EMC should be observed. See IEC 61800-3 and IEC 61800-5-1 for more information on EMC and safety considerations for PDS. See also IEC 61000-5-1 and IEC 61000-5-2 for comprehensive guidance on general EMC installation techniques.

9.1.2 Earthing

9.1.2.1 Objectives of earthing

The objectives of earthing are safety and reliable, interference-free, operation. Traditional earthing is based on electrical safety. It helps to ensure personal safety and limits equipment damage due to electrical faults. For interference-free operation of the PDS more profound methods are needed to ensure that the earthing is effective at high frequencies. This may require the use of equipotential ground planes at building floor, equipment enclosure and circuit board levels.

In addition, correct earthing strongly attenuates electrical machine shaft and frame voltages, reducing high frequency bearing currents and preventing premature bearing failure and possible damage to auxiliary equipment (see Clause 8). The earthing configuration can also have an effect on the phase-to-ground insulation voltage stress levels (see 7.4).

9.1.2.2 Earthing cables

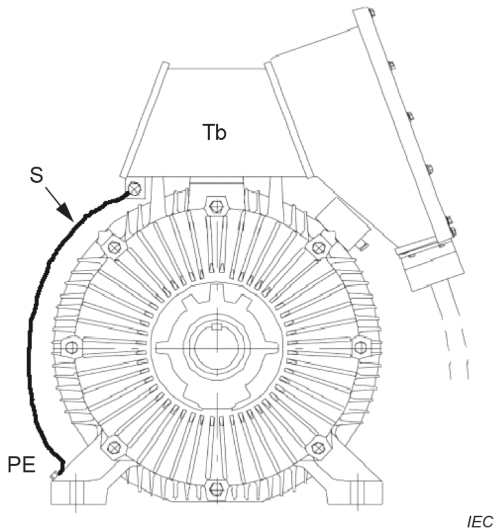
For safety, earthing cables are dimensioned on a case-by-case basis in accordance with local regulations. The appropriate selection of cable characteristics and cabling rules also helps to decrease the levels of electrical stresses applied to the different components of the PDS, and therefore increases its reliability. In addition, the cable types should follow the EMC requirements.

9.1.3 Bonding of electrical machines

Bonding should be implemented in a manner that will not only satisfy safety requirements but will also enhance the EMC performance of the installation. For bonding straps, suitable conductors include metal strips, metal mesh straps or round cables. For these high frequency systems, metal strips or preferably copper braided straps are better. Experience has shown that a typical dimensional length/width ratio for these straps should be less than five.

With electrical machines from 100 kW upwards, the external earthing conditions of the driven machinery may require a bonding connection between the electrical machine frame and the driven machinery. Typical applications are pumps (grounded by water) and gearboxes with central lubrication (grounded by oil pipes). The purpose of this connection is to equalize the potentials and improve the earthing. It should have low inductance, so a metal strip or preferably copper braided strap should be used, and it should follow the shortest possible route. In some cases, additional bonding of the electrical machine components, for example between the electrical machine frame and the terminal box, may be required (see Figure 24).

Where a common lubrication system is used for electrical machine and driven load, care shall be taken to prevent coupling across insulated bearing housings, e.g. by using insulating sleeves and washers for the fasteners, and foundation bolts as well as use of insulating type pipe sections made of ceramic or high density oil resistant PVC.



Key

Tb Terminal box   PE Connection to electrical machine frame   S Bonding strap

Figure 24 – Bonding strap from electrical machine terminal box to electrical machine frame

9.1.4 Electrical machine power cables for high switching frequency converters

9.1.4.1 Recommended configurations

For power levels greater than 30 kW, cables where the single core power and ground conductors are symmetrically disposed may be beneficial to reduce HF bearing currents and EMC effects.

Shielded multicore cables are preferred for lower powers and easy installation. Up to 30 kW electrical machine power and 10 mm^2 cable size, unsymmetrical cables may also be satisfactory but require more care in installation. A foil shield is common in this power range.

To operate as a protective conductor, the shield conductance should be at least 50 % of the phase conductor conductance. At high frequency, the shield conductance should be at least 10 % of the phase conductor conductance. These requirements are easily met with a copper or aluminium shield/armour. Because of its lower conductivity, a steel shield requires a larger cross-section, and the shield helix should be of low-gradient. Galvanizing will increase the high-frequency conductance. If the shield impedance is high, the voltage drop along it caused by high-frequency return currents may raise the electrical machine frame potential with respect to the (grounded) rotor sufficiently to cause undesirable bearing currents to flow (see Clause 8).

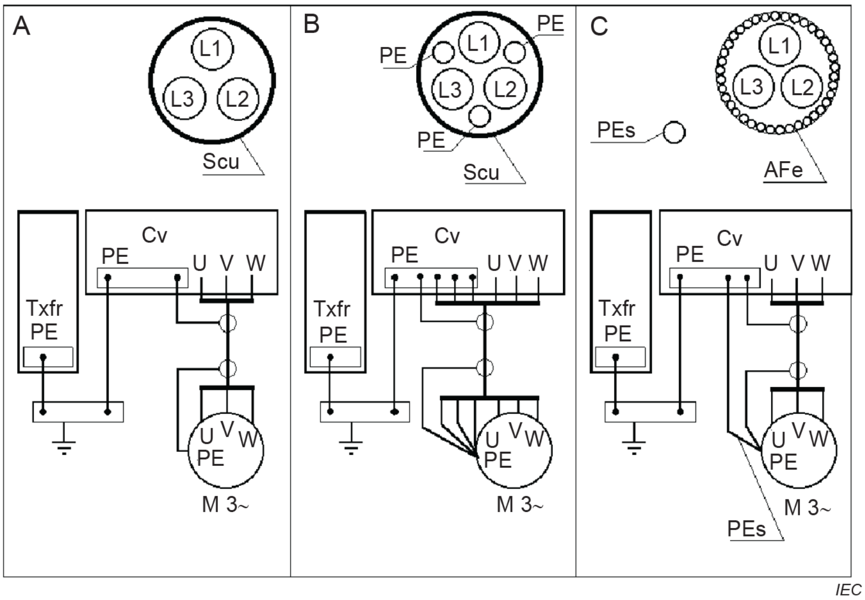
The EMC-effectiveness of the shield may be assessed by evaluation of its surface transfer impedance, which should be low even at high frequencies.

Cable shields should be grounded at both ends. 360° bonding of the shield will utilize the full high-frequency capability of the shield, corresponding to EMC good practice (see 9.1.4.3).

Some examples of suitable shielded cables are:

- three-core cable with a concentric copper or aluminium protective shield (see Figure 30 A). In this case, the phase wires are at an equal distance from each other and from the shield, which is also used as the protective conductor;
- three-core cable with three symmetrical conductors for protective earthing and a concentric shield/armour (see Figure 30 B). The shield of this cable type is for EMC and physical protection only;

  NOTE For low-power systems, a single conductor for protective earthing might be satisfactory.
- three-core cable with a steel or galvanized iron, low pitch, stranded armour/shield (see Figure 30 C). If the shield has an insufficient cross-section for use as a protective conductor, a separate earthing conductor is needed.



Key

Scu	Concentric copper (or aluminium) screen	AFe	Steel armour	Txfr	Transformer	Cv	Converter	PEs	Separate ground wire

Figure 25 – Examples of shielded electrical machine cables and connections

In all cases, the length of those parts of the cable which are to be connected at the frequency converter junction and at the electrical machine terminal box, and therefore have the shield removed, should be as short as possible.

Typically, shielded cable lengths up to about 100 m can be used without additional measures. For longer cables, special measures, such as output filters, may be required. When a filter is used, the above recommendations apply to the cable from the converter output to the filter. If the filter is EMC-effective, the cable from the filter to the electrical machine does not need to be shielded or symmetrical, but the electrical machine may require additional earthing.

Single-core unshielded cables may be suitable for electrical machine cables for higher powers, if they are installed close together on a metallic cable bridge which is bonded to the earthing system at least at both ends of the cable run. Note that the magnetic fields from these cables may induce currents in nearby metalwork, leading to heating and increased losses.

9.1.4.2 Parallel symmetrical cabling

When cabling a high-power converter and electrical machine, the high current requirements may make it necessary to use several conductor elements in parallel. In this case, the appropriate cabling for easy (symmetrical) installation should be done according to Figure 26.

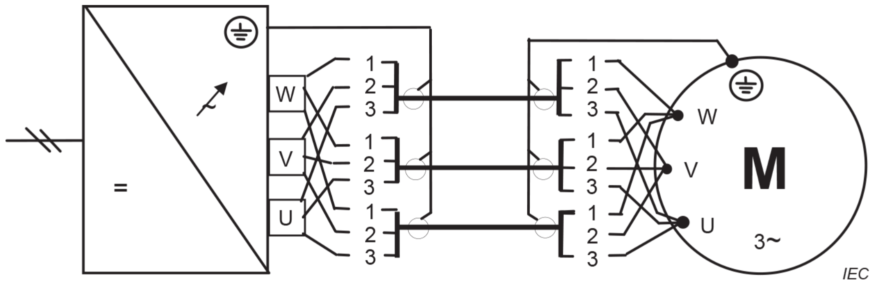
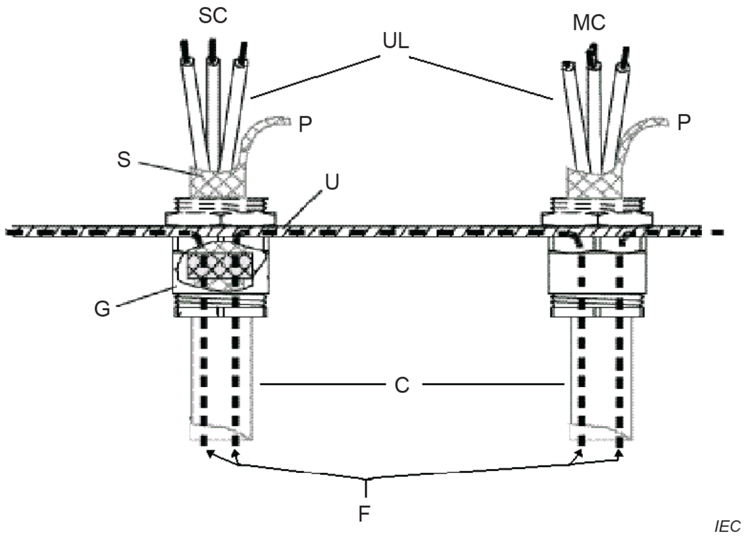


Figure 26 – Parallel symmetrical cabling of high-power converter and electrical machine

9.1.4.3 Cable terminations

When installing the electrical machine cable, it should be ensured that the shield is high frequency (HF) connected to both the converter and the electrical machine enclosure. This requires that the electrical machine terminal box is made of an electrically conductive material like aluminium, iron, etc. that is high frequency electrically connected to the enclosure. The shield connections should be made with 360° terminations, giving low impedance over a wide frequency range from DC to 70 MHz. This effectively reduces shaft and frame voltages and improves EMC performance.

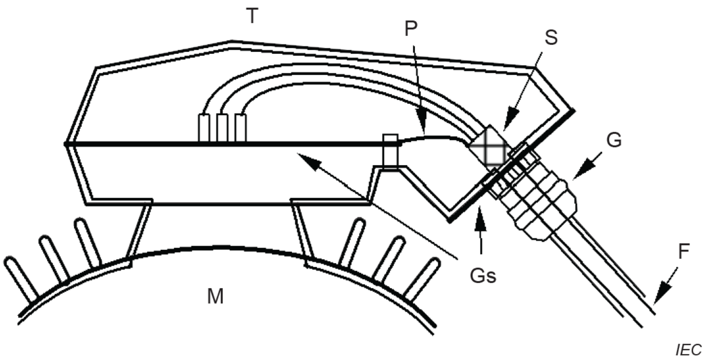
Examples of good practice for the converter and electrical machine ends with lower power are shown in Figure 27 and Figure 28 respectively.



Key

SC Supply cable	MC Electrical machine cable	UL Unscreened length (as short as possible)
S Cable shield	P "Pigtail" (as short as possible)	U Unpainted gland plate
G EMC cable gland	C Cables (outside enclosure)	F Continuous Faraday cage

Figure 27 – Converter connections with 360° HF cable glands showing the Faraday cage

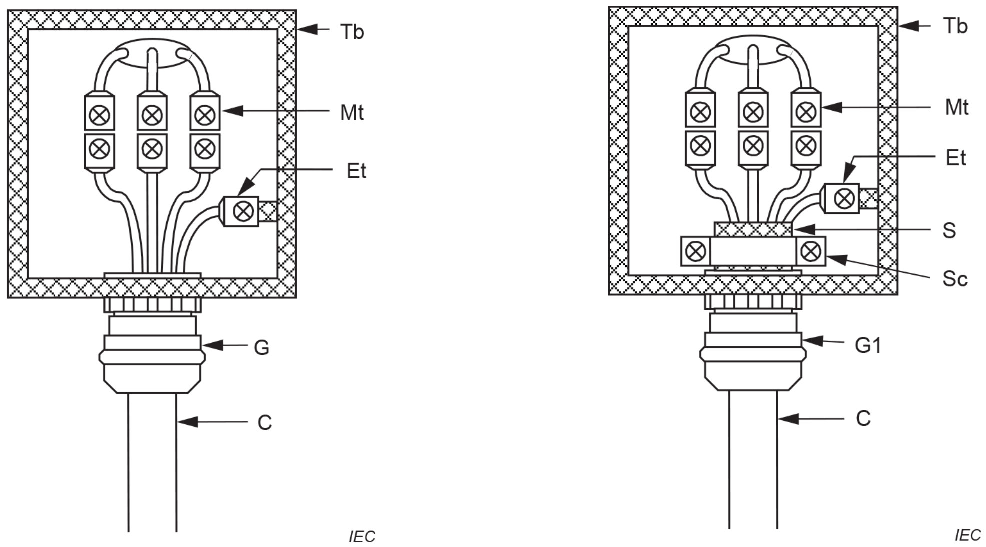


Key

T Terminal box (conductive)	S Cable shield	P Pigtail (as short as possible)	M Electrical machine frame
Gs Conductive gaskets	G EMC cable gland	F Continuous Faraday cage	

Figure 28 – Electrical machine end termination with 360° connection

The shield connections at the electrical machine terminal box should be made with either an EMC cable gland as shown in Figure 29a or with a shield clamp as shown in Figure 29b. Similar connections are required at the converter enclosure.



a) Gland connection **b) Clamp connection**

Key

Tb	Machine terminal box
Mt	Machine terminals
Et	Earthing terminal
S	Cable screen
Sc	Screen clamp
G	EMC cable gland
G1	Non-EMC cable gland
C	Cable

Figure 29 – Cable shield connection

9.1.4.4 Cabling and earthing of auxiliary devices

Auxiliary devices, such as tachometers, should be electrically insulated from the electrical machine in order to prevent the formation of current paths through them, leading to false readings or possible damage. An electrically insulating coupling is a possible solution for a coupling-type encoder. The insulation may be implemented for a hollow-shaft type tachometer by insulating the ball joints or the bar of the engaging arm. The shield of the tachometer cable should be insulated from the tachometer frame. The other end of the shield is grounded at the converter.

Hollow-shaft tachometers with electrical insulation between the hollow-shaft and the tachometer frame will allow connection of the cable shield to the tachometer frame.

The use of double shielded cable is preferred for a pulse encoder. To minimize HF interference problems the shield should be grounded at the encoder end via a capacitor. Single shielded cable may be used with an analogue tachometer.

To prevent unwanted coupling, the cable routing of auxiliary devices should be separated from that of the power cabling.

9.1.4.5 Cabling of integrated sensors

In general, the recommendations for analogue tachometers given in 9.1.4.4 apply to integrated sensors (for example, thermocouples). However, as the wiring to integrated sensors is usually routed in close proximity to the power wiring within the electrical machine, its insulation needs to be adequate for the higher voltages encountered. In these cases, the use of shielded cable may not always be possible.

9.2 Reactors and filters

9.2.1 General

In some installations, for example to reduce voltage stress or to improve EMC performance, the use of reactors or output filters may be beneficial. However, the electrical machine performance may be affected due to the voltage drop across these components.

9.2.2 Output reactors

These are specially designed reactors which can accommodate the PWM waveform and are used to reduce the du/dt and peak voltage. However, care is needed as reactors can theoretically extend the duration of overshoot if incorrectly selected – particular care is needed with ferrite core inductors. In the case shown in Figure 30a, the addition of the reactor has increased the rise-time to around 5 µs and reduced the peak voltage to 792 V. Normally, the output reactor is mounted within the converter cabinet. Output reactors can also be used to compensate for cable charging currents and may be used for electrical machine cable lengths up to many hundred metres on larger drives.

9.2.3 Voltage limiting filter (du/dt filter)

In this case, a design consisting of capacitors, inductors and diodes or resistors may be used to limit the du/dt, drastically reducing the peak voltage and increasing the rise-time. In the example shown in Figure 30b, the peak voltage is reduced to 684 V with a du/dt of 40 V/µs. Some increased losses of 0,5 % to 1,0 % should be accommodated, and there may be a reduction in breakaway and breakdown torque.

9.2.4 Sinusoidal filter

A special design of low pass filters allows the high frequency currents to be shunted away and the resulting voltage waveform on the output to the electrical machine becomes sinusoidal. The phase-to-phase output voltage (differential) for approximately 1,5 periods of the corner point frequency is shown in Figure 30c. Generally, there are the following two types of sinusoidal filters.

a) Design with both phase-to-ground and phase-to-phase filtering.

b) Design with only phase-to-phase filtering.

These filters are expensive and have also other limitations. They prevent the electrical machine voltage from exceeding 90 % of the supply voltage (thereby de-rating the converter). They also will not be suitable for applications that require high dynamic performance.

9.2.5 Electrical machine termination unit

An electrical machine termination unit can be connected at the electrical machine terminals. Its purpose is to match the electrical machine impedance to that of the cable, thereby preventing voltage reflections at the electrical machine. For the example illustrated in Figure 30d the peak voltage is now only 800 V with a rise-time of 2 µs. Typically, these filters add around 0,5 % to 1,0 % losses.

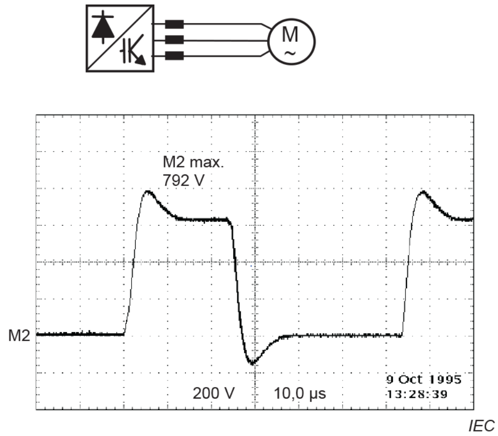


Figure 30a – Output reactor (3 % voltage drop)

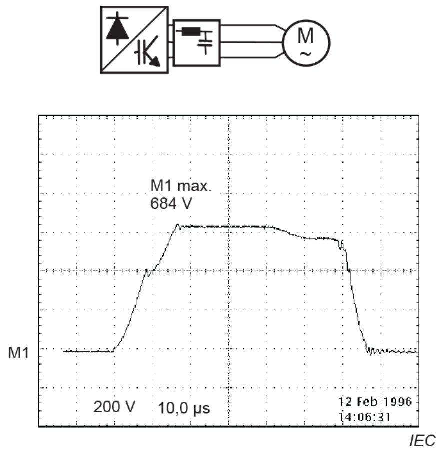


Figure 30b – Output d*u*/d*t* filter

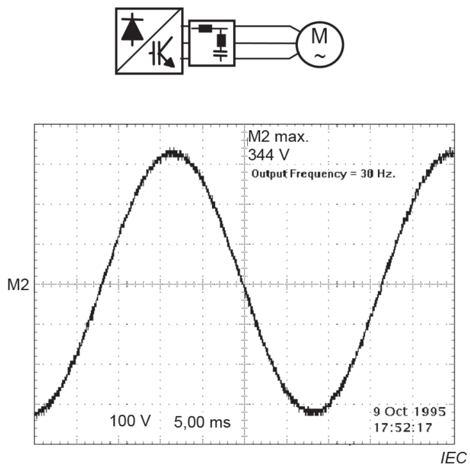


Figure 30c – Sinusoidal filter

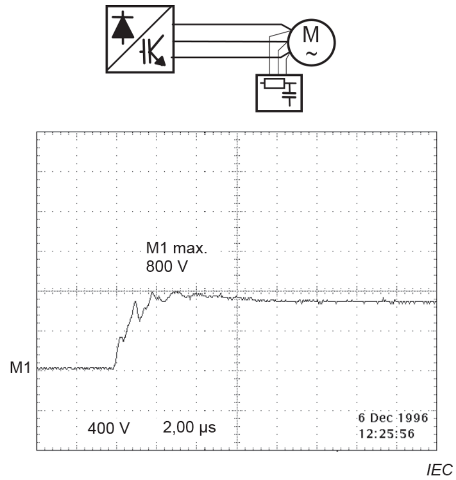


Figure 30d – Electrical machine termination unit

Figure 30 – Characteristics of preventative measures

9.3 Power factor correction

Power factor correction at the input of the converter should never be undertaken without harmonic analysis.

The use of power capacitors for power factor correction on the load side of an electronic control connected to an induction electrical machine is not recommended; damage to the control may occur and power factor capacitors are not generally rated for the high frequencies to which they are subjected.

Power factor correction at the input of a voltage source converter can be achieved by the use of a converter with an active front end.

See IEC TS 62578.

9.4 Integral electrical machines (integrated electrical machine and drive modules)

When a converter is mounted inside the electrical machine enclosure, i.e. in the electrical machine terminal box or in a separate compartment forming an integral part of the total electrical machine enclosure construction, where both converter and electrical machine utilize a common cooling system, the whole unit is called an integral electrical machine.

It has some clear benefits for the user:

- easy installation and commissioning (usually no special cables or additional bonding or earthing);
- common integral enclosure helps to fulfil the EMC-requirements (a Faraday cage). It also reduces the risk of shaft grounding current;
- no long cables or leads between the converter and the electrical machine keep the voltage reflections and peak voltage low and predictable but du/dt is not reduced;
- compact solution i.e. savings in total required space and installation;
- a single supplier for electrical machine and converter, i.e. clear responsibility for the PDS.

But it has some disadvantages too:

- depending on the application, the environment may be very hostile for the converter electronics (high degree of enclosure protection required and shock and heat/cold resistant circuit boards and components);
- the technical life of the main components may differ significantly (electrical machines some 15 to 20 years but converters only 5 to 10 years).

10 Additional considerations for permanent magnet (PM) synchronous electrical machines fed by voltage source converters

10.1 System characteristics

The benefits of a PDS consisting of a voltage source converter and a permanent magnet synchronous electrical machine instead of an induction electrical machine are:

- lower VA rating of the converter, as a synchronous electrical machine can be rated for unity power factor;
- losses in the electrical machine might be lower. For system efficiency review the losses in the converter shall be taken into account;
- reduced machine size, compared with an induction electrical machine of the same rating;
- in a properly designed electrical machine, the rotor losses are minimal and therefore will have no effect on the thermal behavior of the rotor;
- simpler cooling arrangements of the electrical machine, due to minimal rotor losses.

On the other hand, operation in the field-weakening range requires special measures, as the field of the PM needs to be reduced by the stator current, which might require a reduction of the available output power.

10.2 Losses and their effects

The statements of Clause 5 remain valid.

As PM synchronous electrical machines do not usually have a damper winding, the harmonic currents can, depending on the rotor design, cause eddy currents in the permanent magnets or in the solid parts of the rotor (or both). The heating of the magnets due to increased stator losses and the eddy currents in the magnets can cause permanent demagnetization.

10.3 Noise, vibration and torsional oscillation

The statements of Clause 6 remain valid.

10.4 Electrical machine insulation electrical stresses

The statements of Clause 7 remain valid.

When the electrical machine is operating in regenerating mode, care should be taken that the back EMF does not exceed the capabilities of the installation. This should be a part of the installation risk analysis under particular fault circumstances, for example control loss during deep field weakening, or short circuit of the wiring, etc.

10.5 Bearing currents

The statements of Clause 8 remain valid.

NOTE There may also be an additional bearing in the feedback device.

10.6 Particular aspects of permanent magnets

Permanent magnet demagnetization during electrical machine operation usually occurs because of abnormally large demagnetizing current peaks, due for instance to fault conditions or motor control loss. Heating of permanent magnets can increase this risk, making demagnetization happen at lower current values.

11 Additional considerations for cage induction electrical machines fed by high voltage source converters

11.1 General

In general, the statements made with respect to low-voltage electrical machines supplied by voltage source converter*s* are valid for medium-voltage or high voltage electrical machines and converter*s* as well. Nevertheless, some differences exist.

11.2 System characteristics

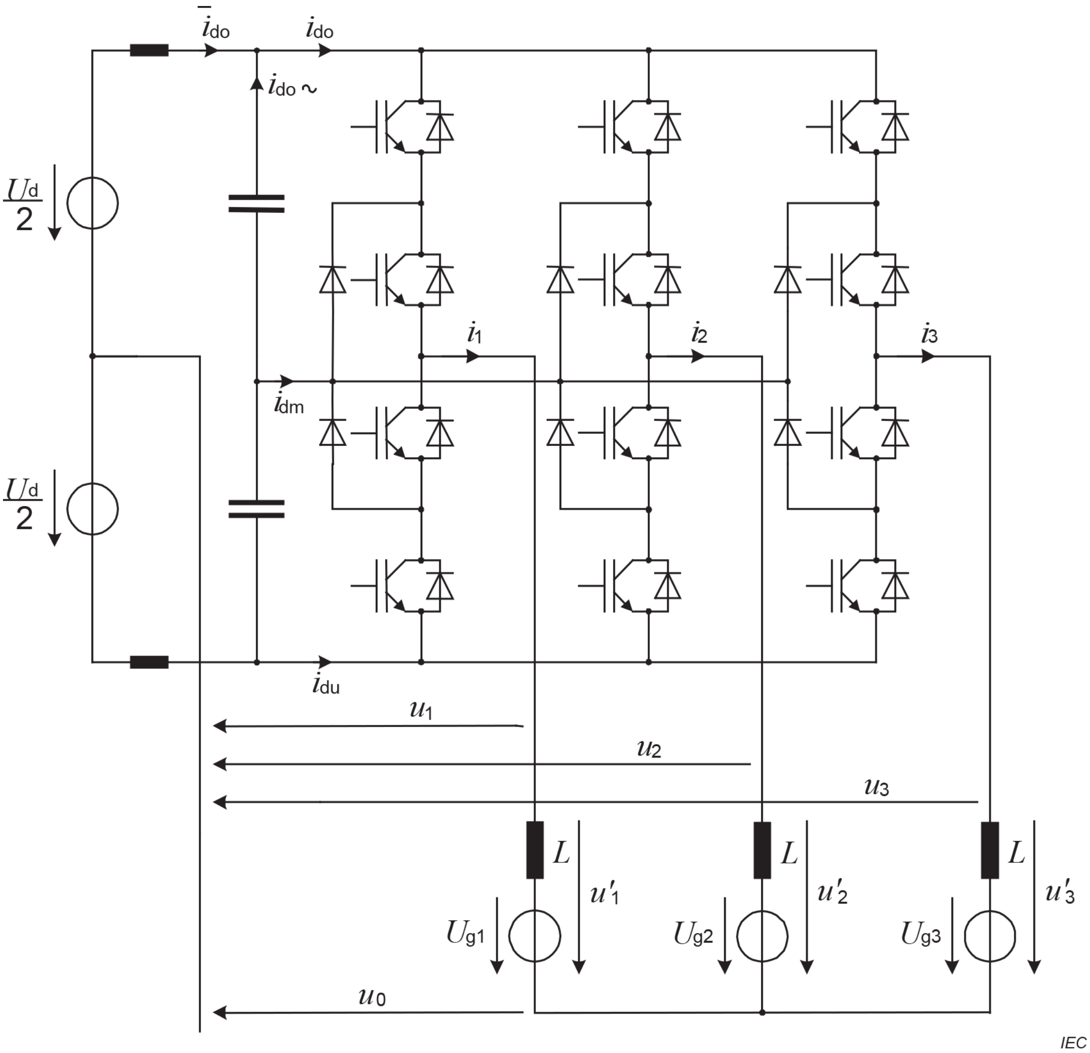


Figure 31 – Schematic of typical three-level converter

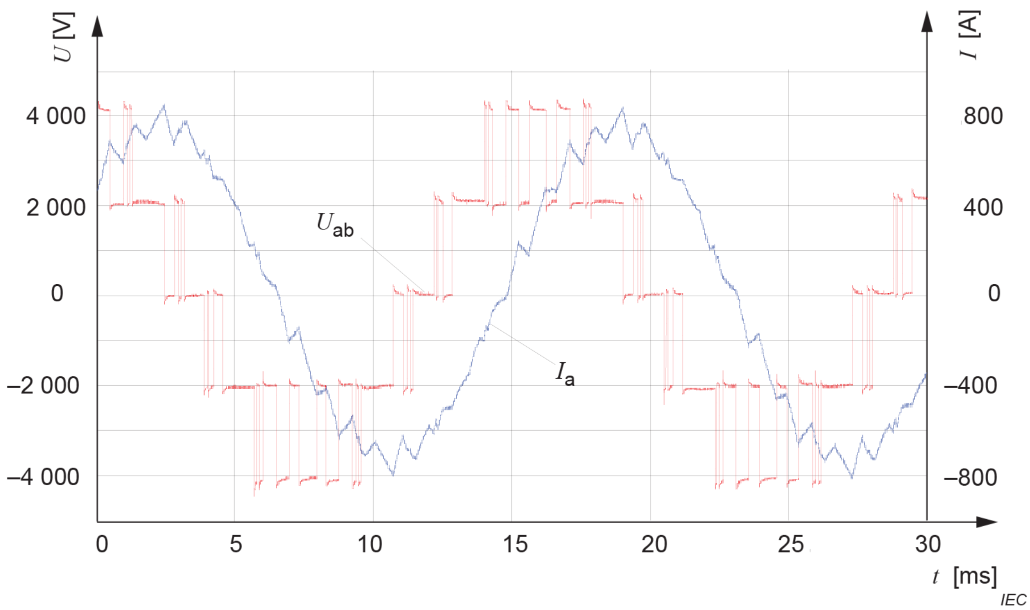


Figure 32 – Output voltage and current from typical three-level converter

Medium voltage converters might be three-level or multi-level converters, which means that they have more than one semiconductor power device in each branch of the inverter bridge connected in series (Figure 31). For a three-level converter, for example, the line-to-line voltage can be impressed in 5 different values ($-U_d$, $-½ U_d$, 0, $½ U_d$, U_d) instead of only 3 values ($-U_d$, 0, U_d) possible for two-level converters. On the one hand, this allows a better waveform of the output voltage, reducing harmonic currents (by approximately 50 % for each increase in level Figure 32). On the other hand, the pulse frequency of medium voltage converters is lower than that of low-voltage converters, reducing the frequency of the voltage harmonics and tending to increase the harmonic currents.

11.3 Losses and their effects

11.3.1 Additional losses in the stator and rotor winding

Each type of converter impresses a certain extent of harmonic current or of harmonic voltage causing harmonic currents into the electrical machine. The additional high frequency losses generated in the stator winding due to these harmonic currents depend significantly on the height of the strands of the stator winding and its arrangement in the cross-sectional area of the slots, since the effective a.c. resistance of the winding increases strongly with frequency and with the strand height. Where the level of harmonic currents is low, a special design of the strands or strand transposition is usually not necessary for electrical machines fed from voltage source converters.

As mentioned in 11.2, three-level or multi-level converters impress a better (more sinusoidal) waveform of the output voltage, reducing harmonic currents. High voltage converters usually have a lower pulse frequency, which reduces the additional iron losses but tends to increase the harmonic currents. Due to the numerous factors influencing the additional losses in the electrical machine, a general statement is not possible.

As discussed in 5.2, the rotor winding will also generate additional losses due to harmonics which are further increased by the skin effect.

11.3.2 Measurement of additional losses

For drives with power ratings in the megawatt range, a test of the complete PDS in the manufacturer's test field is often not economic, since it consumes a significant amount of time and cost. Nevertheless, the additional losses have to be considered for the overall efficiency of the PDS and for the thermal design of the electrical machine.

For a properly designed PDS, it is usually sufficient to rely on the calculated values. This calculation shall consider the main influencing factors.

By agreement between manufacturer and customer, tests may be performed according to the IEC 60034-2 series.

11.4 Noise, vibration and torsional oscillation

As explained in 11.3.2, it is usually not economic for PDS with power ratings in the megawatt range to perform measurements in a test site with the electrical machine supplied from a converter. If required, noise and vibration measurements of the complete PDS should be performed during the commissioning at site but may be considerably influenced by the performance of the driven equipment.

For electrical machines with power ratings in the megawatt range and maximum operating speeds exceeding approximately 2 500 r/min, it is, in many cases, not possible or not beneficial to achieve a rotor dynamic design with the first lateral critical speed above the maximum operation speed. Consequently, it is – especially in case of a speed control range with a width of more than 50 % of the rated speed – not possible to keep the speed control range free of lateral critical speeds.

Since the operation at, or close to, a lateral critical speed can cause inadmissible shaft vibrations, it is recommended to skip these resonant frequencies. In cases where it is required to fix the skip bands in the design phase, their width might be some 100 r/min due to the limited accuracy for the prediction of the lateral critical speeds and the damping of the complete shafting. The skip band width can be kept significantly smaller, when determined during commissioning with the knowledge of the real critical speeds; this procedure might be preferable.

11.5 Electrical machine insulation electrical stresses

11.5.1 General

A critical parameter that determines the first-turn electrical stress is the maximum rate of voltage change (du/dt) on the winding (Figure 33). For low-voltage systems, the applied voltage will generally be within the range of 400 V to 690 V, and so the du/dt can be sufficiently specified by the rise-time. For high-voltage systems, there is a greater range of applied voltage, and so it is necessary to consider the actual du/dt.

NOTE Typical values of du/dt are 3 kV/µs to 4 kV/µs.

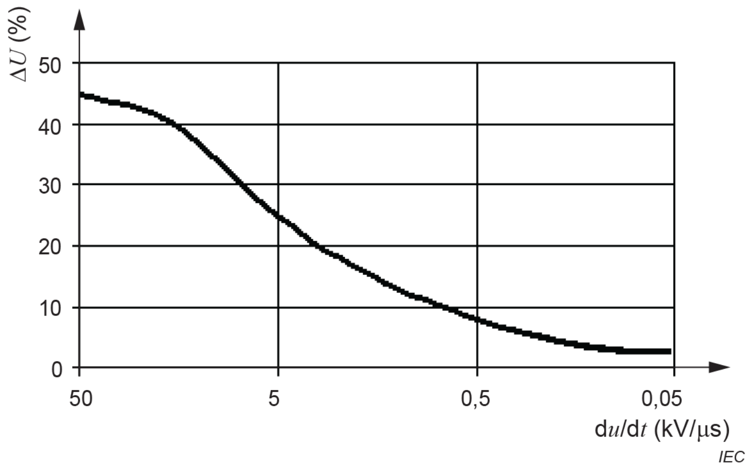


Figure 33 – Typical first turn voltage ΔU (as a percentage of the line-to-ground voltage) as a function of du/dt

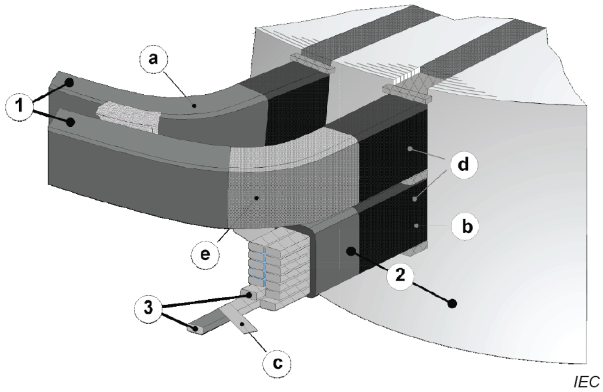
11.5.2 Electrical machine terminal overvoltage

In addition to the factors mentioned in 7.1 to 7.3, the overvoltage appearing at the terminals of a converter-fed electrical machine also depends on the number of converter stages. Voltage impulse levels shall be determined by the system integrator according to IEC TS 61800-8. The result shall be communicated to the electrical machine manufacturer so the insulation system can be designed accordingly.

11.5.3 Stator winding voltage stresses in converter applications

11.5.3.1 General

Converter-fed electrical machine form-wound stator windings, for sinusoidal voltage ratings of 2,3 kV and above, exposed to short rise-time surges with significant magnitudes and high frequencies, can be subjected to additional voltage stresses at the locations 1, 2 and 3 illustrated in Figure 34.



Key

1 Location of phase-to-phase insulation

2 Location of phase-to-ground insulation

3 Location of turn-to-turn insulation

a Phase insulation/end-winding insulation

b Ground insulation

c Strand insulation

d Slot voltage stress control layer

e End-winding voltage stress control layer (stress grading)

Figure 34 – Medium-voltage and high-voltage form-wound coil insulating and voltage stress control materials

The effects of these additional stator winding voltage stresses on the stator winding insulation system are discussed in 11.5.3.2 to 11.5.3.5. It is important that the electrical machine designer is aware of the characteristics of converter output voltage waveforms, as seen at the electrical machine terminals, to ensure that these are taken into account during stator winding design.

11.5.3.2 Voltage stresses between adjacent conductors in line end coils

If there are air voids next to or between the turn insulation, failure from partial discharges (PD) can occur if inadequate turn insulation is used. Such failures result from continuous exposure to high-voltage surges having rise-times below 2 µs. Short rise-time voltage surges will have a non-uniform voltage distribution across the winding line end coils to significantly elevate turn-to-turn voltages stresses. Most electrical machine manufacturers are aware of this and use suitable strand or turn insulation and good vacuum pressure impregnation (VPI), or hot pressed resin rich coil insulation processes, in stator windings rated 2,3 kV and above. This approach is effective in minimizing the risk of turn failures from PD caused by continuous high frequency surges and air voids around the winding conductors.

11.5.3.3 Voltage stresses between conductors and ground

Voltage stresses between conductors and ground are influenced by the PDS earthing configuration. Care should be taken to avoid excessive dielectric heating of insulating materials, caused by high-frequency capacitive currents, which can raise the stator winding temperature and increase the rate of thermal ageing.

In addition, the properties of semi-conductive voltage stress control coatings can be degraded by this additional heating. Once the voltage stress relief coating degrades the process is accelerated by the ozone generated by PD activity.

11.5.3.4 Voltages between adjacent line end coils in different phases

Phase-to-phase PD can occur if the voltage stress between such coil components is greater than about 3 kVpeak/mm. This is more likely in converter-fed electrical machines due to the higher transient repetitive voltages that appear on each phase. Appropriate end-winding spacing is required for converter-fed electrical machines, or the voltage potential between coil surfaces in different phases should be reduced.

11.5.3.5 Across the semi-conductive/grading material voltage stress control layers

High-voltage electrical machines with form-wound coils may have a grading layer of material, normally having a non-linear resistivity, that overlaps the stress-control layer at each end, in order to attenuate high-voltage stresses at the interface between the stress-control layer and the end-windings (see Figure 34). Operating experience has shown that conventional voltage stress control materials can degrade fairly rapidly as a result of high frequency voltages significantly increasing dielectric heating in both the conductive and grading materials. The effect is exacerbated because the higher frequencies also cause the silicon carbide materials to be less effective in linearizing the voltage along the surface of the coils which tends to concentrate the heating to a shorter area near the core ends. Manufacturers and researchers are now looking at capacitive grading systems to overcome this problem which should be identified by IEC 60034-18-42 stator winding insulation system qualification tests.

11.6 Bearing currents

The statements of Clause 8 remain valid.

12 Additional considerations for synchronous electrical machines fed by voltage source converters

12.1 System characteristics

The benefits of a PDS consisting of a voltage source converter and a synchronous electrical machine instead of an induction electrical machine are as follows.

- Lower VA rating of the converter, as a synchronous electrical machine can be rated for unity power factor.
- Losses in the electrical machine might be lower. For system efficiency review the losses in the converter shall be taken into account.
- Higher pull-out torque in the field-weakening range of the converter.

All statements of 11.2 remain valid.

12.2 Losses and their effects

The statements of 11.3 remain valid.

In addition it shall be mentioned that the losses in the damper cage of synchronous electrical machines are not identical in all bars.

12.3 Noise, vibration and torsional oscillation

The statements of 11.4 remain valid.

12.4 Electrical machine insulation electrical stresses

The statements of 11.5 remain valid.

12.5 Bearing currents

The statements of 11.6 remain valid.

13 Additional considerations for cage induction electrical machines fed by block-type current source converters

13.1 System characteristics (see Figure 35 and Figure 36)

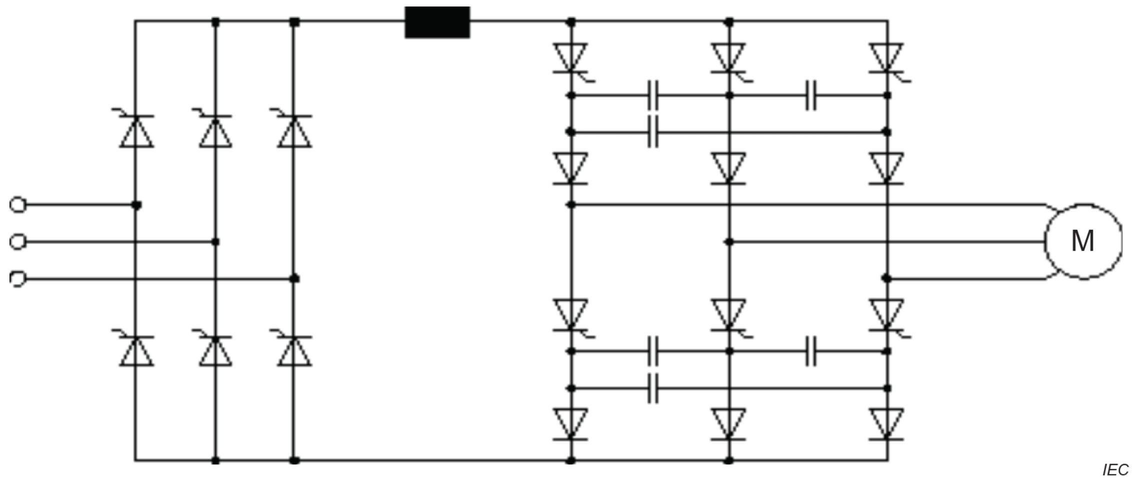


Figure 35 – Schematic of block-type current source converter

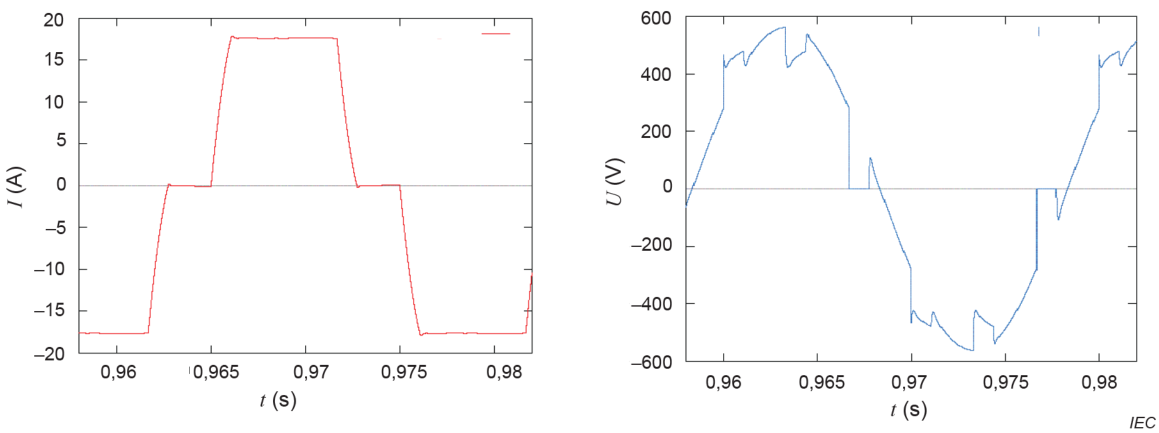


Figure 36 – Current and voltage waveforms of block-type current source converter

The converter is characterized by:

- a controlled, line-commutated rectifier connected to the power supply;
- a large reactor in the intermediate circuit to smooth the DC current and;
- a controlled, self-commutated inverter connected to the electrical machine.

The electrical machine currents are block-type (120° blocks), containing harmonics of order n = –5; +7; –11; +13; etc . The plus/minus sign indicates whether the magnetic field, which is excited by the harmonic currents, rotates in the same sense as the field of the fundamental current or reverse. The amplitudes of the harmonics are proportional to $1/n$. The phase-voltage of the electrical machine contains transients at all commutation intervals of the current.

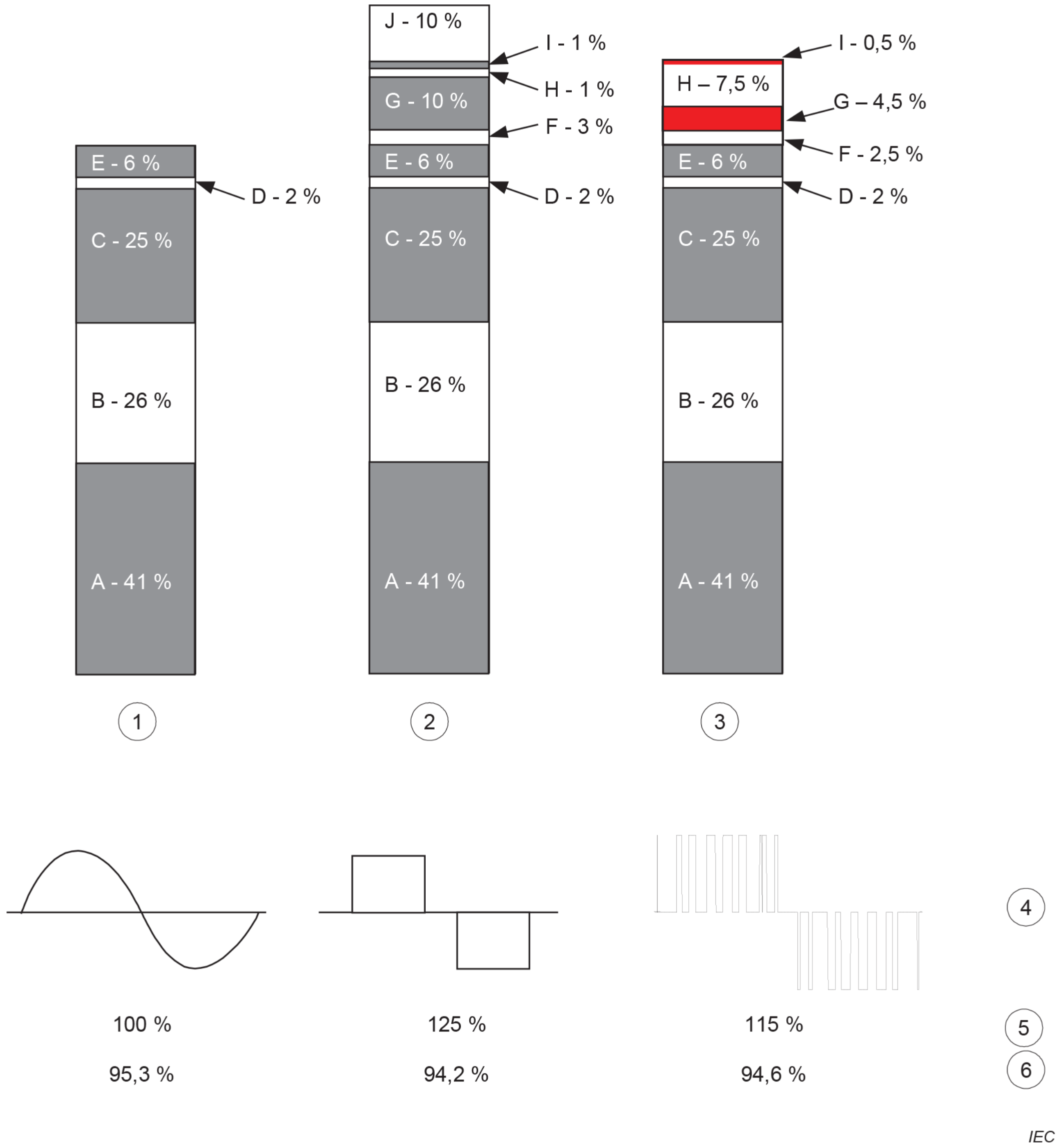
The stator winding is part of the commutation circuit. Therefore, the electrical machine should be designed for low leakage inductance; the converter manufacturer shall be familiar with its approximate value for proper design of the commutation capacitors.

13.2 Losses and their effects

Even though the phase voltage is nearly sinusoidal, the sudden jump of the currents during commutation is associated by fast changes of the slot leakage flux, causing additional iron losses (so-called commutation losses) especially in the stator teeth.

Another important part of extra losses caused by harmonics are the winding losses in the cage due to the high frequencies approximately $(n - 1)f_1$ of the harmonic currents. Therefore the extra losses of an electrical machine supplied by a current source converter at full load, are typically higher than the extra losses of the same electrical machine supplied by a PWM inverter. The columns in Figure 37 show, as an example, the calculated loss composition of a specific electrical machine (frame size 315 M; design N) when supplied both from different converter*s* with different harmonic content and from a sinusoidal supply. The example illustrates the relative importance of the different types of losses for the converter systems most widely used today. The comparison cannot be transferred to other converter-fed cage induction electrical machines and other types of converter*s* (with different modulation schemes and pulse frequencies). To facilitate comparison in Figure 37, the fundamental voltages and currents during converter operation are assumed to be the same as under rated conditions.

According to Figure 37, the harmonic losses are higher for supply by current source converter*s* than by voltage source converter*s*. The difference diminishes at partial load, because the harmonic losses are constant for voltage source converter supply, but the harmonic losses increase with load for current source converter supply.



Losses caused by corner point frequency	Losses caused by harmonics
E Frictional losses	J Commutation losses
D Additional load losses	I Additional load losses
C Iron losses	H Iron losses
B Rotor winding losses	G Rotor winding losses
A Stator winding losses	F Stator winding losses

Key

1 Sinusoidal voltage

2 Current source converter

3 Voltage source converter with carrier modulation (switching frequency ≈ 3 kHz)

4 Time dependence of the impressed quantity

5 Losses

6 Efficiency

Figure 37 – Influence of converter supply on the losses of a cage induction electrical machine (frame size 315 M, design N) with rated values of torque and speed

The statement given in 11.3.1 on the influence of the strand height of the stator winding on the additional losses in the stator winding due to current harmonics is of special importance for electrical machines fed from current source converters. For strands of electrical machines with power ratings in the megawatt range designed for sinusoidal voltage supply, a height of some millimetres is not unusual. In order to reduce the additional losses, it is recommended to design electrical machines fed from current source converters with smaller strands and to limit the number of parallel connected strands placed above each other in the slot to three. Alternatively, a transposition of the strands either within one coil (bar) or between adjacent coils might be required.

Subclause 11.3.2 is valid for these electrical machines as well.

13.3 Noise, vibration and torsional oscillation

Additional magnetic tones are produced by the interaction of the fundamental waves (number of pole pairs p) of the harmonics and of corner point frequency. The waves of tensile stress, which are responsible for the noise emission of magnetic tones, are of the modes $r = 0$ or $r = 2p$ and of the frequencies $f_r = (n \pm 1)f_1$ (n = 1, 2, 3, etc.) respectively. Since harmonics of order $n > 13$ are of small amplitude, they can normally be neglected. Therefore, the frequencies of the additional tones are less than 1 kHz, far away from the resonance frequencies of the stator which are much higher. The increase of noise at converter supply in comparison to the operation of the same electrical machine at sinusoidal supply (at the same values of U_1, f_1 and load) is relatively small (in the range 1 dB to 5 dB).

The most important negative effect of current source converters on the performance of cage induction electrical machines is the generation of pulsating torques of relatively high amplitudes. In a six pulse circuit, the oscillating torques with 6 and 12 times the operational frequency (f_1) are of practical importance; their amplitudes are in the order of 15 % (frequency $6 \times f_1$) and 5 % (frequency $12 \times f_1$) of the rated torque. In addition, oscillating torques are excited by harmonics which are based on the ripples of the DC current in the intermediate circuit; these torques are of the frequency $6(f_1 - f_p)$ and $12(f_1 - f_p)$, where f_p is the power frequency of the mains. The current ripple in the intermediate circuit $(i_{max} - i_{min})/i_{DC}$ is typically of the order of 10 %, and results in pulsating torques having amplitudes of a few per cent of the rating torque.

Because of these pulsating torques, a careful torsional analysis of the complete rotating assembly is highly recommended. If one of the torsional critical speeds coincides with the frequency of a pulsating torque within the speed setting range, continuous operation at this speed is not permitted and may be dangerous. This is especially the case when couplings of small damping coefficient (metal-elastic couplings) are used. In such cases skipping of a small frequency band is advisable.

13.4 Electrical machine insulation electrical stresses

As already stated in 13.1, the phase-voltage of the electrical machine contains transients at all commutation intervals of the current. These transients stress the winding insulation; however, since the inverters are usually equipped by thyristors, the peak values and the rise-time are not so extreme that an enhanced insulation system would be necessary.

13.5 Bearing currents

It is proven by tests and practical experience that current source converter supply has little impact on the shaft voltage. No special measures for bearing protection are necessary.

13.6 Additional considerations for six-phase cage induction electrical machines

The term six-phase winding is often paraphrased by the text “two identical three-phase windings shifted against each other by the circumferential angle 30°/*p*”. The two windings are supplied by two identical current source converter*s* as described in 13.1, but having a phase difference of the fundamental output currents of 30°.

This arrangement has the advantage, that the air-gap fields, which are excited by the harmonic currents of order n = –5 and n = 7 by both windings, eliminate each other. As a consequence, no rotor losses are produced by these harmonics and also no pulsating torques of 6 times the corner point frequency exist. The frequencies of the pulsating torques follow the expression $12kf_1$ (k = 1; 2; etc.).

The formula of the frequencies of the pulsating torques, based on the DC current ripple, remains unchanged (see 13.3).

All statements of 13.1 to 13.5 regarding other effects of current source converter*s* remain valid.

14 Additional considerations for synchronous electrical machines fed by LCI

14.1 System characteristics

Synchronous electrical machines with static or brushless excitation can also be supplied by current source converter*s* (LCI). For the electrical machine, this type of supply is the same as a block-type current source converter. A damper winding is required to reduce the pulsating torques caused by the harmonic fields. If a solid-pole construction is used, the induced eddy currents have the same effect as a damper winding.

The rectifier connected to the power supply is line-commutated.

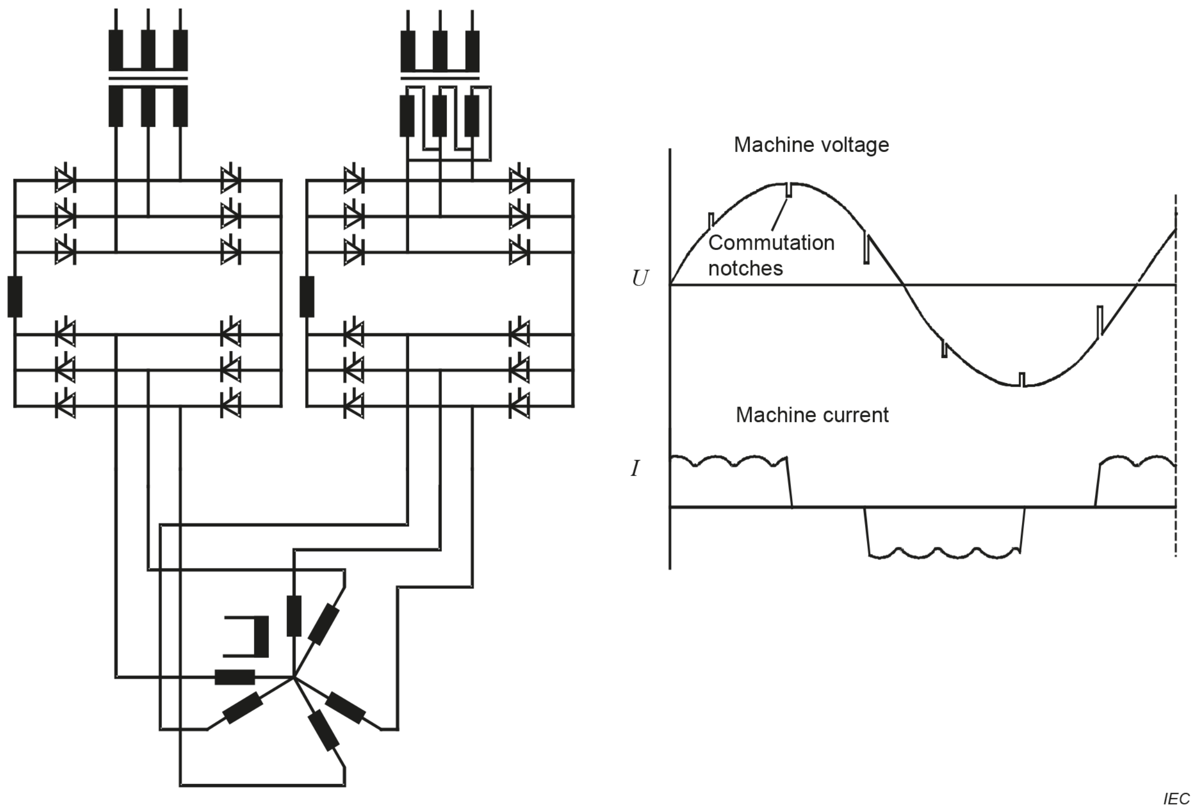


Figure 38 – Schematic and voltage and current waveforms for a synchronous electrical machine supplied from a current source converter

The inverter connected to the electrical machine is load commutated. The synchronous electrical machine is operated overexcited in order to supply the reactive power which is necessary for the commutation of the inverter. In this case, the reactive power is not supplied by the converter, whereas in the case of an induction electrical machine both the active and the reactive power shall be supplied by the converter. Therefore, the converter of a synchronous electrical machine can be designed to be smaller and less expensive. In addition, the commutation is as simple as that of the line-side inverter.

Another distinctive feature is that the synchronous electrical machine can produce reactive power only when it is turning, not at standstill. Therefore, starting would be impossible without additional measures such as DC link pulsing, whereby the reactive power, which is necessary for the operation of the commutation, can be supplied at very low speed, including standstill.

The six-phase arrangements shown in Figure 38 can be regarded as two six-pulse current source converters, each feeding one of the electrical machine's two three-phase windings. Alternatively, a real 12-pulse arrangement can be designed by using a three-winding transformer between the two six-pulse converters and a three-phase electrical machine. This arrangement eliminates in the transformer the frequencies $-5f_1$, $+7f_1$, $-17f_1$, $+19f_1$, etc. (reducing additional losses in the stator winding). In addition, this arrangement allows the possibility to synchronize the electrical machine direct with the mains, in case speed adjustment is not required for some operation modes.

Electrical machines with eight or more poles are commonly salient pole electrical machines with laminated poles or pole shoes. A damper cage is incorporated in the pole shoes. For electrical machines with four or six poles, a laminated cylindrical rotor, or a rotor with laminated or solid salient poles is common. Two-pole electrical machines always have a cylindrical rotor, with either a laminated or a solid active part of the rotor. Cylindrical rotors always have a damper cage; in solid salient pole rotors damper currents will flow in the solid surface of the pole shoes. The copper damper cage of cylindrical rotors has the benefit of lower additional losses in the cage and somewhat lower pulsating torques compared to electrical machines with solid salient poles. Nevertheless, a general statement on the overall efficiency of both designs is not possible, since salient pole electrical machines naturally have lower windage losses than electrical machines with cylindrical rotor.

14.2 Losses and their effects

The statements of 13.2 and 13.6 remain valid.

The additional losses due to current harmonics require a proper design of the damper winding, especially in case of a three-phase electrical machine supplied by a 6-pulse converter. Otherwise, these additional losses can have a negative influence on the temperature of the field winding.

As already stated in 14.1, a real 12-pulse converter arrangement will lead to a reduction of the additional losses in the stator winding.

14.3 Noise, vibration and torsional oscillation

The statements of 13.3 and 13.6 remain valid.

14.4 Electrical machine insulation electrical stresses

The statements of 13.4 remain valid.

14.5 Bearing currents

The statements of 13.5 remain valid.

15 Additional considerations for cage induction electrical machines fed by pulsed current source converters (PWM CSI)

15.1 System characteristics (see Figure 39)

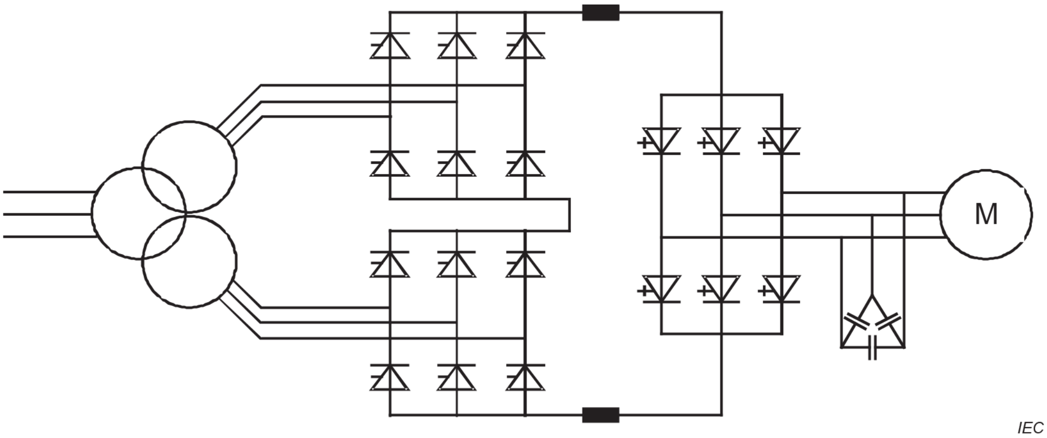
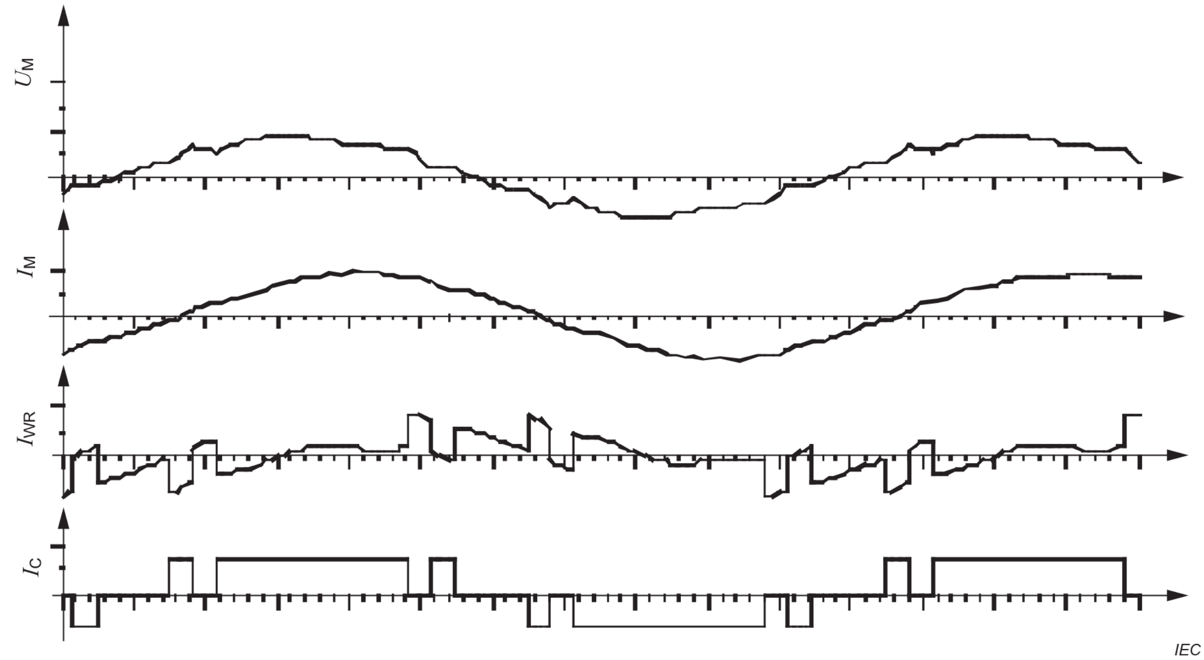


Figure 39 – Schematic of pulsed current source converter



Key

U_M	Electrical machine voltage	I_{WR}	Filter capacitor current
I_M	Electrical machine current	I_c	Inverter output current

Figure 40 – Voltages and currents of pulsed current source converter

A significant reduction of the harmonic voltages and currents caused by a current source converter can be achieved by a PWM of the inverter output current combined with filter capacitors at the converter output. Figure 40 shows that both electrical machine current and electrical machine voltage are close to a sinusoidal form. Nevertheless, the remaining harmonics need to be considered.

15.2 Losses and their effects

Due to the relatively low content of voltage and current harmonics, the additional iron losses are smaller than for electrical machines supplied by voltage source converters. There are no significant commutation losses to be expected. The additional losses in the stator winding are comparable to electrical machines supplied by voltage source converters, so that a strand transposition is usually not required.

NOTE Although the harmonic voltages of PWM CSI converters are lower than those of voltage source converters, their frequencies are also lower. It is therefore not possible to make a general statement concerning the relative amplitudes of the harmonic currents.

The statements of 11.3.2 remain valid.

15.3 Noise, vibration and torsional oscillation

The statements of 11.4 remain valid.

15.4 Electrical machine insulation electrical stresses

The statements of 13.4 remain valid.

15.5 Bearing currents

The statements of 13.5 remain valid.

16 Wound rotor induction (asynchronous) electrical machines supplied by voltage source converters in the rotor circuit

16.1 System characteristics

Slip-ring electrical machines with rotor supply from a voltage source converter are customary to be used as wind-turbine generators in the power range above 1 000 kW, but may be used also in electrical machine applications. The converters are usually equipped as an active infeed for power factor correction (see IEC TS 62578 for more details). The stator winding is connected directly to the mains. These electrical machines are also referred to as doubly fed electrical machines.

The speed of the drive is fixed by the formula $n = (f_1 \pm f_2)/p$, where f_1 is mains frequency and f_2 is converter output frequency. By this means, operation as electrical motor or generator is possible at speeds below and above the synchronous speed f_1/p.

The main advantage of this system is that the converter does not need to be rated for the full rated power of the induction electrical machine, but for a fraction only, which depends on the maximum slip and the reactive power requirement in case of power factor correction. Furthermore, it is possible to use a low voltage two level converter for the rotor circuit, even though the stator winding is for high voltage.

16.2 Losses and their effects

As the stator winding is connected directly to the mains, the harmonic content of the stator current is very low and additional losses are negligible. For the rotor winding, the general statements of Clause 5 apply. Special consideration needs to be given to the current displacement in the rotor winding: For wound rotor induction electrical machines with ratings in the MW range, the rotor winding is usually made form solid copper bars. As the rotor frequency of doubly fed electrical machines can exceed 10 Hz, the losses in the rotor winding can be significantly increased by current displacement, which increases the effective ohmic resistance of the rotor winding. This effect needs to be considered as well for the losses due to current harmonics in the rotor winding caused by the converter.

16.3 Noise, vibration and torsional oscillation

The statements of 11.4 remain valid.

16.4 Electrical machine insulation electrical stresses

As the stator winding is connected directly to the mains, its insulation stress does not differ from normal fixed-speed electrical machines. For the rotor winding, the statements of 11.5 remain valid.

16.5 Bearing currents

Due to the direct capacitive coupling, the bearing voltage ratio BVR is much higher in the case of electrical machines connected to a converter in the rotor circuit than in the case of a converter connected to the stator. Therefore, the bearings are endangered. An earth brush and insulation of both bearings, to provide an impedance of at least 100 Ω at 1 MHz, are recommended. To protect the driven equipment and its auxiliaries, the coupling should be electrically isolating.

17 Other electrical machine/converter systems

17.1 Drives supplied by cyclo-converters

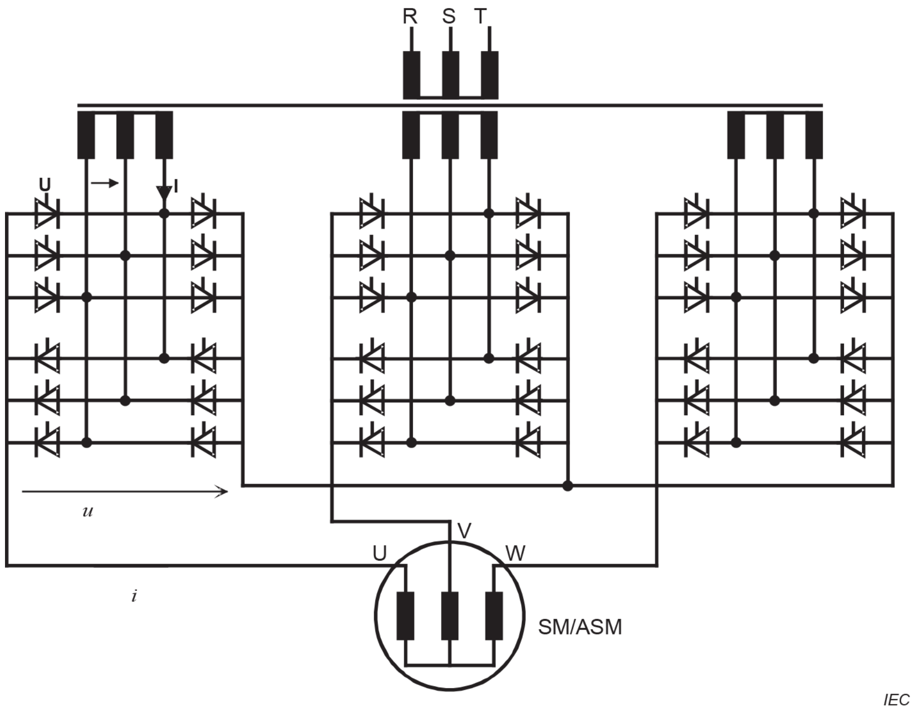


Figure 41 – Schematic of cyclo-converter

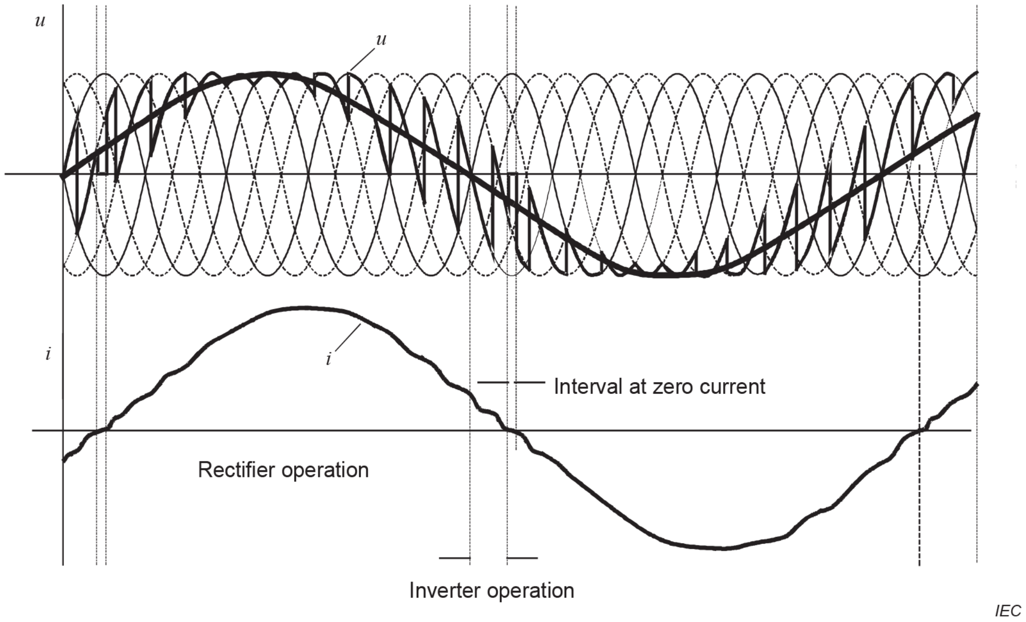


Figure 42 – Voltage and current waveforms of a cyclo-converter

A cyclo-converter has no intermediate d.c. circuit. It consists of three partial converters for each of the three electrical machine phases. These partial converters are controlled independently with the aim to generate a sinusoidal output current by directly connecting the electrical machine phase for a certain period of time with one of the mains. The output frequency has to be lower than 50 % of the frequency of the mains for the cyclo-converter of Figure 41. For synchronous electrical machines, a unity power factor is possible. See also Figure 42.

Even though the current is controlled to be nearly sinusoidal, cyclo-converter operation implies voltage impressing for the electrical machine. Consequently, it is not beneficial to supply an electrical machine with two circumferentially shifted winding systems with phase shifted voltages from two converter systems. In cases where two converter systems are used, their output voltages should be in phase and the electrical machine winding systems should not be circumferentially shifted. Alternatively, the converter systems can be connected in series to form a 12-pulse converter. Since the converters are usually equipped by thyristors, an enhanced insulation system is usually not required.

The frequencies of the voltage and current harmonics follow the rule:

$$f = (1 + 6g_1)f_1 + g_2 z_p f_{\text{mains}}$$

where

z_p is the number of pulses of the converter (6 or 12);

g_1, g_2 = 0; ±1; ±2; etc.,

resulting in oscillating torque frequencies $f = 6g_1f_1 + g_2z_pf_{\text{mains}}$. The magnitude of the torque oscillations is fairly low but increases with increasing converter output frequency. Even though the harmonic components for $g_2 = 0$ are often not mentioned in literature, they are present resulting from the small time periods without current between positive and negative half-wave.

17.2 Wound rotor induction (asynchronous) electrical machines supplied by current source converters in the rotor circuit

These arrangements are known as sub-synchronous (or super-synchronous) converter cascade (SSCC). The stator of the wound rotor induction electrical machine is directly connected to the mains. The slip-rings are connected to a current source converter, thus being able to feed the power sP_{δ} (s = slip, P_{δ} = power consumption from the mains minus stator losses) that appears electrically in the rotor circuit, back to the mains.

The advantage of this arrangement compared to converter-fed cage induction electrical machines is that the rated power of the converter required for a SSCC is only the fraction s_{max} of that required in the latter case, assuming that the speed control range is limited from $(1 - s_{max})n_0$ to n_0.

Since the rotor currents are block-type like the stator currents of cage induction electrical machines supplied by current source converters, the statements of 13.1 apply.

The rotor current contains harmonics of the order n = +1, –5, +7, –11, +13, etc., causing additional losses in the rotor winding. In the cases where the rotor winding of wound rotor induction electrical machines usually is of the bar type, these additional losses will significantly rise due to current displacement. Since the converters are usually equipped by thyristors, an enhanced insulation system is commonly not required.

The harmonic currents result in oscillating torques with frequencies of $6sf_1$ and multiples, requiring a careful design with respect to torsional resonances of the rotating string.

An earth brush is recommended to prevent negative impacts on bearing currents.

18 Special consideration for standard fixed-speed induction electrical machines in the scope of IEC 60034-12 when fed from voltage source converter and motor requirements to be considered a converter capable motor

18.1 General

A converter capable motor as defined in 3.17 is a motor designed for across-the-line start and is suitable for operation on a converter without special filtering. See Figure 43.

NOTE 1 Such motors include IEC Design N, NE, NEY, H, HE, or HEY, or NEMA Design A, B, or C which may be subject to energy efficiency regulation in the EU, North American and other locations.

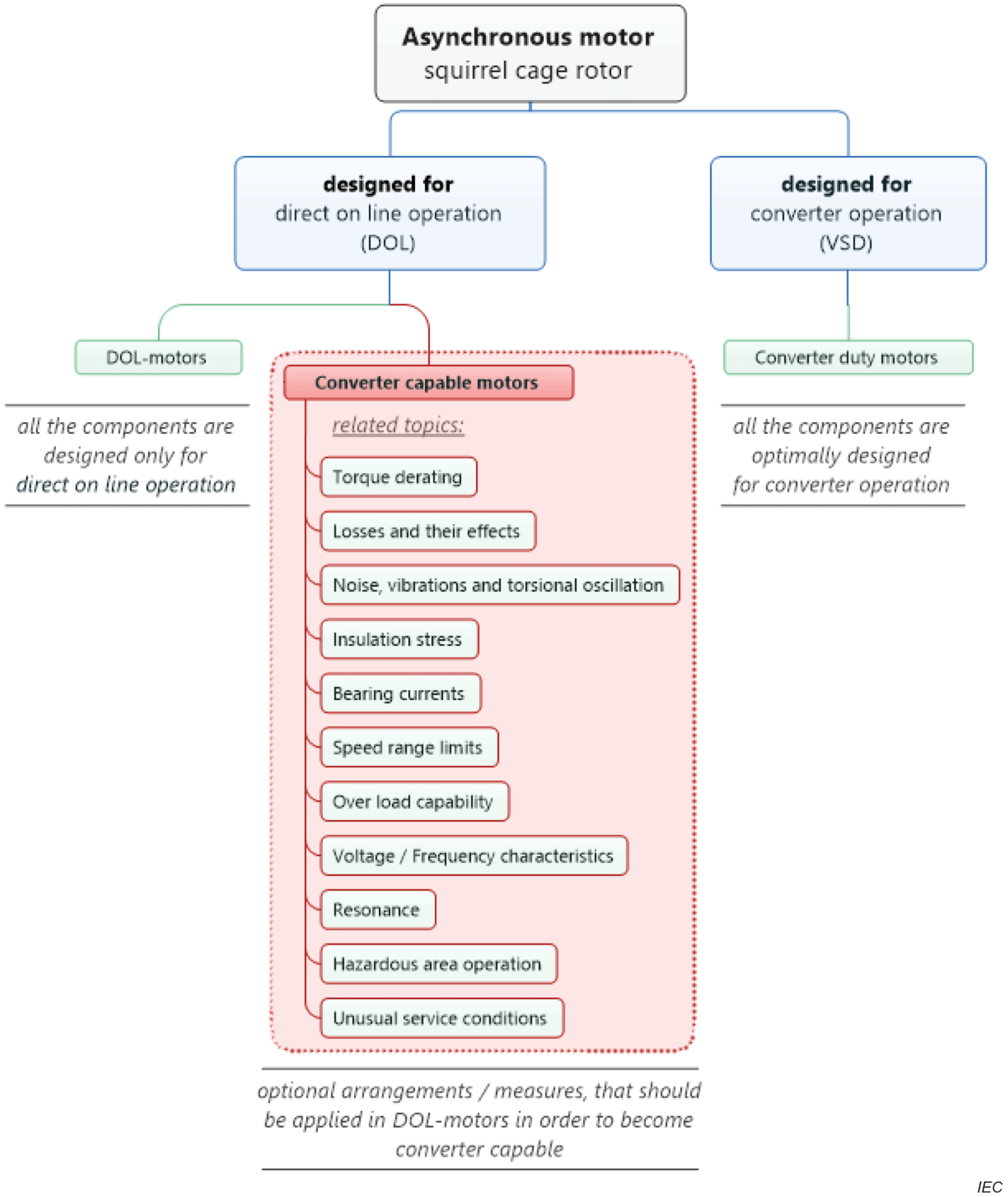


Figure 43 – Diagram comparing converter capable motor to converter duty motor

Standard fixed-speed induction electrical machines in the scope of IEC 60034-12 when fed from voltage source converter, Motors rated 1 MW and smaller are commonly stocked in inventory and are defined as suitable for operation on a converter. The IVIC class of C/B has been defined in accordance with IEC 60034-18-41 with a drive that produces an impulse to the motor of IVIC class C/B or insulation system qualified in accordance with IEC 60034-18-42 with a drive that produces an impulse to the motor of IVIC class 5/4 to ensure standard motor insulation can operate. It is good to have this understanding, but that is not the only performance character that is critical for a converter capable motor. Other performance characteristics shall also be defined. This Clause 18 defines the considerations and requirements/expectations when using a machine not specifically designed for converter capability and expectations of a converter capable motor.

NOTE 2 Some systems use an insulation system with spike-resistant wire qualified in accordance with IEC 60034-18-42.

18.2 Torque derating during converter operation

18.2.1 General

When the electrical machine is supplied from a converter at the electrical machine rated frequency, the available torque is usually less than the rated torque on a sinusoidal voltage supply due to increased temperature rise (harmonic losses). An additional reason for the reduction may be the voltage drop of the converter. Maintaining of the rated torque may reduce insulation service-life.

The full-line curve in Figure 44 refers to a converter producing approximately the same fundamental electrical machine flux as at sinusoidal supply where flux is directly related to voltage. The electrical machine manufacturer can determine the temperature rise for this operating point if the harmonic spectrum of the converter is known. The temperature rise depends on the individual electrical machine design and the type of cooling (e.g. IC 01 or IC 411). When determining the derating factor, the thermal reserve of the particular electrical machine is important. Taking all these influences into account, the derating factor at rated frequency typically ranges from 0,8 to 1,0.

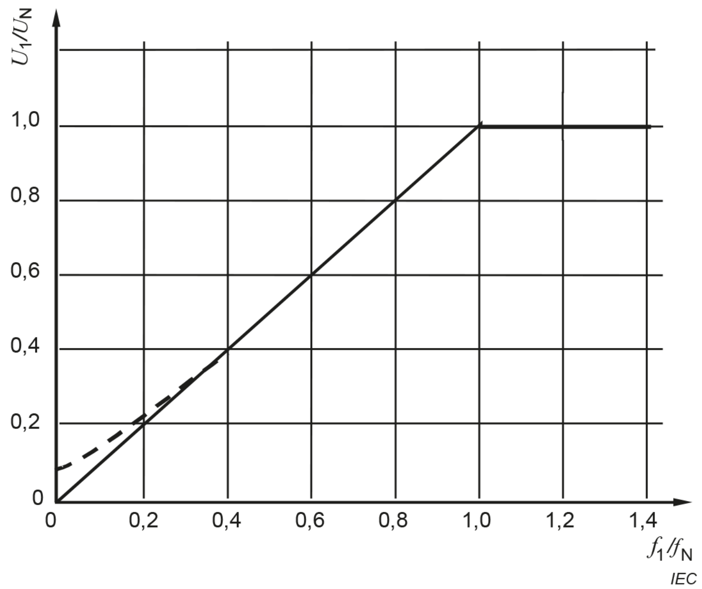


Figure 44 – Fundamental voltage U_1 as a function of operating frequency f_1

Frequently, in practice, the converter rating does not imply that the fundamental flux at rated frequency is the same as on sinusoidal voltage. The consequence is an additional torque deviation, the values of which depend on the individual parameters.

Within the speed setting range below the synchronous speed at electrical machine rated frequency, applying a constant ratio U_1/f_1 leads to a constant pull-out torque only if the stator winding resistance is negligible in comparison with the electrical machine reactance. To compensate for the effect of the electrical machine stator resistance, some converter controls are designed to have a characteristic in accordance with the dashed line in Figure 44. At low speeds, higher torques are generated than in the absence of such a compensation.

Above the 1,0 p.u. operation point of voltage and frequency in Figure 44, the converter output voltage is generally constant as the frequency increases (field-weakening range). In the event of this occurring within the frequency operating range, then the derating factor will change with a rapid reduction in torque capability similar to the characteristic shown in Figure 45 f_1/f_N = 1,0.

Figure 45 shows an example of a derating curve for a typical electrical machine. Such a curve can be declared by the electrical machine manufacturer, if the harmonic spectrum and the voltage-frequency characteristics of the converter are known. With respect to the different cooling (IC 01 or IC 411) and ventilation methods (self-circulation cooling or independent cooling) it is not possible to produce a curve which applies to all cases. The derating is normally reduced as the switching frequency increases. Figure 45 is with self-circulation.

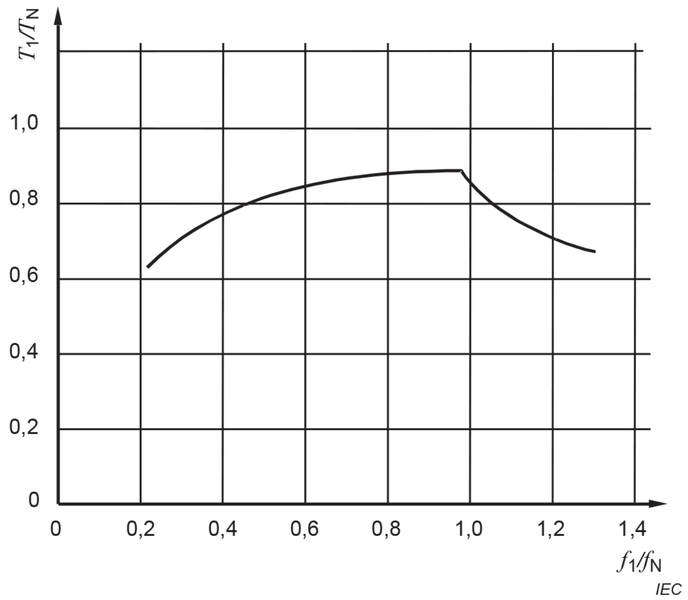


Figure 45 – Torque derating factor for cage induction electrical machines of design N, IC 411 (self-circulating cooling) as a function of operating frequency f_1 (example)

18.2.2 Self-cooled motors

For self-cooled (e.g., IC411) motors, operation in an extended speed range implies modified air flow and cooling effectiveness. A typical behavior of continuous torque vs. speed curve for self-cooled motors is shown in the C_S curves in Figure 1. Derating required to meet design operating temperature is shown in Annex D, Figure D.2.

When a motor is declared as converter capable, the manufacturer should state in documentation the amount of torque derating to be expected for operation at speeds lower than rated, as well as the maximum operating speed.

Depending on the specific motor application, operating a self-cooled motor at low speed has different effects.

- Constant torque applications – When reducing the operating speed while maintaining a constant output torque, because of reduced cooling an increase in the motor operating temperature is to be expected. The decrease in iron losses due to reduced frequency is normally not enough to compensate for the reduced cooling. Typically, only a limited speed range is suitable for continuous torque operation. A general rule cannot be given. Users should carefully evaluate motor applicability case-by-case, using manufacturer information about torque derating at low speed.
- Variable torque applications (linear torque or quadratic torque) – In these kinds of applications, even if air flow is reduced at low speed, motor losses are also significantly reduced because of the lower required output. Typical operating speed range in this case is larger and can extend to very low speed values.

NOTE It assumes that the control scheme behaves ideally.

- Constant power applications – Constant power applications will normally cover speeds greater than rated and operate in field-weakening range. In such operating conditions, air flow is increased with respect to the rated operating point and the upper speed limit is typically related to mechanical limitations e.g., bearings, fan and rotor construction.

18.2.3 Non self-cooled motors

Motors with different cooling arrangements (e.g. IC416, independent cooling, or IC410, natural cooling) have no or negligible reduction of cooling effectiveness due to reduced operating speed, hence they do not suffer from the above described limitations. They are typically declared to have constant continuous torque versus speed curve (see curve *C*x shown in Figure 1) and their speed range can be expected to extend to very low values.

NOTE 1 Since iron losses are reduced at lower supply frequency, the output capability of such motors can actually increase at low speed. Normally this is not declared, in order to preserve design margins; however, the effect can be remarkable and is typically exploited in high dynamic variable speed applications where a compact design is mandatory, e.g., servomotor applications.

NOTE 2 In case of double cooling circuit (e.g. IC611, IC616, IC666), circulation in each circuit can be arranged as either self-circulation or independent circulation. The effect of reduced speed depends on the specific arrangement and manufacturer provided data should always be used to determine the available speed range.

18.3 Losses and their effects

For a motor to be defined as being converter capable, the temperature shall stay within the in thermal class of the motors as defined by the manufacturer with the harmonics delivered to the motor from a voltage source inverter (VSI). The expected increase in losses and temperature rise of the motor could range up to 15 % to 25 % percent dependent on converter topology and carrier frequency as compared to a pure sinusoidal input. See Annex D for guidance on derating based on harmonic content. Many times, a class 130 (B) rise motor on a sinusoidal power supply may be allowed to run thermal class 155 (F) rise on the converter.

18.4 Noise, vibrations and torsional oscillation

The statements of Clause 6 remain valid.

18.5 Electrical machine insulation electrical stresses

18.5.1 General

The mechanisms of how the converter operation stresses the electrical machine insulation are given in Clause 7.

The combination of fast switching inverters with cables will cause peak voltages due to transmission line effects. For electrical machines rated at voltages less than or equal to 500 V AC the insulation system should typically give satisfactory life when subjected to peak voltages. Care shall be taken to avoid variable speed applications that involve rapid speed changes as these can cause regenerative voltages at the converter output up to twice the rated electrical machine volts.

For electrical machines rated over 500 V AC, supplied from a fast switching inverter, an enhanced insulation system and/or filters at the converter output (designed to increase the rise-time and/or to limit the peak voltages) may be required.

The actual impulse voltage to be expected at the electrical machine terminal can be determined as described in IEC TS 61800-8 where U_{LL} is equivalent to V_{PP}.

The determined repetitive impulse voltage shall be less than that shown in Table 4. The actual impulse voltage can be influenced by the topology of the PDS (power supply system input and output converter section, filtering section, cabling section and grounding conditions). The impulse withstand capability of older insulations systems may not be able to withstand these levels. It is recommended to contact the electrical machine manufacturer to confirm what levels are acceptable.

In some PDS impulse voltage line to ground $\hat{U}_{LG}$ may exceed impulse voltage line to line, therefore $\hat{U}_{LG}$ shall also be less than given in Table 4.

18.5.2 Converter capable motor

As stated in IEC 60034-1, for electrical motors with a rated voltage below 1 000 V, the manufacturer can assign an impulse voltage insulation class (IVIC) according to IEC 60034-18-41 for the insulation system. Unless otherwise stated by the manufacturer, the insulation system shall be suitable for IVIC C for phase-to-phase and IVIC B for phase-to-ground, Or in accordance with IEC 60034-18-42 (IVIC) 5/4.

18.6 Bearing currents in converter capable motors

The mechanism for bearing currents is discussed in Clause 8.

The converter capable motors are those electrical motors that are optimally developed for direct on-line operation which either their default components are able to cope with the converter operation or their modular design allows the utilization/replacement of specific components (such as insulated bearings) as an additional option which shall be applied for enabling converter operation. For electrical motors within the scope of this specification the insulation of an antifriction bearing can be achieved by replacement with an insulated bearing of the same dimensions

For these electrical motors, if a proper grounding system is installed, experience shows that:

- When properly installed, electric motors, within the scope of this document and with shaft heights up to 100 mm, there is minimal occurrence of bearing failures caused by converter operation due to low parasitic capacitances. Even for shaft heights up to 225 mm, bearing failure is seldom experienced, up to 280 mm sporadically. Nevertheless, the dielectric stress on the bearings varies widely with the type of control algorithm, pulse pattern and especially with the switching frequency of the converter. To minimize bearing failures, measures should be taken according to Table 6.
- To minimize bearing failures, electric motors with shaft heights of 280 mm and above may have provision for at least one insulated bearing, with impedance of at least 100 Ω per bearing at 1 MHz, or other provisions per Table 6. For motors with shaft height 315 mm and above, shall have at least one insulated bearing, with impedance of at least 100 Ω per bearing at 1 MHz, and consider other provisions per Table 6.

  NOTE 1 A common practice to enable converter operation is the installation of an insulated bearing in the non-drive end (NDE). The practice of insulating both electrical motor bearings (to include drive end (DE)) depends on the installation site (e.g., plant where the whole drive system is installed). The installation should be examined by an expert, including input power supply, the driven electric motor (insulation of the coupling), the converter, and the grounding system (possibly use of an earthing/bonding brush).

- For electrical motors within the scope of this document and with shaft heights above 280 mm, for which the insulation of the electrical motor bearing is not possible or not desirable, it is recommended either:
  – to reduce the $\mathrm{d}u/\mathrm{d}t$ of the converter output voltage,
  – or to use a converter with a filter designed to reduce the zero-sequence component of the phase voltages (common-mode voltage).

  And (additionally),

  – to use common mode inductivities (chokes) which can reduce the excitation, i.e. the common mode current. The attachment of nanocrystalline iron cores at the output of the inverter is also a preventive measure. For that, the iron cores have to be installed in all three phases (without ground).

NOTE 2 The proper grounding system can be achieved with the following measures:

- use of low impedance HF grounding of the motor and low impedance HF connection of the load;
- use of symmetrically shielded motor connecting cables;
- use of equipotential bonding between motor and load;
- ensuring all connection to be done through the largest possible surface.

18.7 Speed range mechanical limits

18.7.1 General

As a rule, converter fed motors operate over a wide speed range (which may include operating speeds above and/or below base speed) rather than at a single fixed speed during its service life. For the motor to be able to operate successfully throughout the required speed range both the electromagnetic and the thermomechanical limitations of the motor design have to be observed.

18.7.2 Maximum speed

The restrictions for high-speed operation of a converter fed motor concerns both electromagnetic and mechanical issues. The electromagnetic limitations correspond to the motor torque capability (18.3). The mechanical limitations concern the motor safe operation, which depends on the rotational capacity of the bearings and on the rotation speed factor of the lubricant grease and the rotor structure. The safe operation of the self-ventilated motor also depends on the structure of the fan.

The maximum safe operating speed is obtained from the rating plate of the electrical motor. The limits of 9.6 of IEC 60034-1:2022 apply if nothing else has been stated. Depending on the electrical motor design, the operation at higher speeds may be permitted, but this possibility should be verified by the manufacturer.

When operating at speeds above rated speed, noise and vibration levels will increase. It may also be required to refine the balance for acceptable operation above rated speed.

Operation at speeds close to the maximum safe operating speed for extended periods of time may cause considerable shortening of the service life of the bearings. Moreover, the shaft seals and/or the regreasing intervals (or the grease service life in the case of greased-for-life bearings) may be affected.

18.7.3 Minimum speed

For motors built with antifriction bearings, the main restriction for low speed operation normally lies on the thermal performance of the motor (particularly in case of self-ventilated motors), due to the loss of efficiency of their cooling systems in this condition.

For motors using hydrodynamics bearings as discussed in 4.3.5, 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.

Torque derating factors (18.2) shall be carefully applied especially in the case of constant torque (CT) loads. For operation at very low speeds, voltage boost may be also necessary to compensate for the voltage drop within motor windings. In case of open loop control, low speed operation may be limited by restrictions related to the converter.

On flexible shaft motors, one or more critical speeds may exist within the required operating speed range. Operation close to these speeds can raise the vibration levels above safe limits and should be therefore avoided.

18.8 Overload torque capability

At times motors are required to run overload for short durations to meet either overload conditions or starting high torque loads.

Generally, a motor should be operated at rated torque which is calculated by rated kW and rated speed shown on its nameplate. However, some application may require overload operation in a short time not to exceed 60 s. In case, followings should be taken into consideration;

- Motor should have enough maximum torque which excess over-load torque requirement, so that it can keep operation without stoppage or loss of synchronism.
- Both motor and converter should have enough temperature capacity to allow increase of current in a short time. In general, thermal capacity of motor is bigger than that of converter, so that over-load capability of converter is mainly to be considered.

18.9 Excess overload current limits

18.9.1 General

In many cases, converter defines a limitation of overload current and time, such as 150 % – 60 s. The limitation is to be considered for motor start, stop, and overload operation. The higher overload current can be a duration shorter than the time required to start or stop the motor. Therefore, if rapid speed change is required, overload current limit of converter and the inertia of motor/load are to be considered.

18.9.2 Converter capable motor

Short duration over-load is not typically a limitation of a motor it can often be a converter limitation. A converter capable motor can handle 150 % load for 60 s without damage to the motor. Motor shall be allowed enough time to cool to normal operating temperature before repeating the overload. Smaller motors may overheat and be damaged if overload is frequently repeated.

18.10 Volts/Hz ratio and voltage boost

For converter capable motor see 4.3.

18.11 Resonance

For converter capable motor there should be no undamped resonances within the defined speed range that would adversely affect the vibration and mechanical performance of the motor.

The manufacturer may provide a speed range that avoids speeds of known resonances when operating on a massive foundation. As resonances are a system concern other speeds may have to be avoided if the foundation introduces additional resonances.

18.12 Hazardous area operation

18.12.1 General

Application of converter capable motors in hazardous locations requires that all equipment meet applicable local codes. Additional considerations when operating on a converter rather than sine wave power include:

a) Motor may experience increased temperature rise effects due to the harmonics produced by the converter supply. These are a result of increased iron, copper, and hysteresis loss. The overall rise is dependent on the harmonic content of the converter output waveforms – voltage and current – and the specific machine design.

b) Motor may experience increased temperature rise effects due to reduced speed. This is primarily due to the reduction in airflow, developed pressure, or both. This is particularly important for constant and/or linear torque loads. When auxiliary fans are used, they should be designed for the area classification where they will be installed.

c) Shaft voltages occur on all motors regardless of power source. Elevated shaft voltages will occur on converter-fed machines due to the presence of common-mode voltage (CMV) at the machine terminals. The manner and degree to which the shaft voltages and the resulting bearing currents are expressed at the machine bearings (electrical bearing load) is dependent on the specific drive topology, power cabling between drive and machine, grounding, etc. See details in Clause 8. The maximum CMV associated with the specific drive topology for a given application should be obtained from the drive manufacturer; use this value to obtain the resulting shaft voltages due to capacitive coupling effects

d) Refer to IEC 60079-7 for Zone 2 locations.

18.12.2 Converter capable motor

A converter capable motor in a Zone 2 location shall be able to perform within the limits listed below when operating in the following common converter-fed application listed below. The limits apply within the speed range defined on the nameplate or in the documented literature.

The motor rating should be selected to avoid overload conditions. The following parameters describe the requirements for an application of a converter capable machine and its converter source in a Zone 2 location involving equipment handling materials with auto-ignition temperatures in excess of 200 °C. Equipment manufacturers (converter and motor) and users should discuss each application to ensure the conditions described herein are satisfied.

a) Motor defined with a class 130 (B) temperature rise should have a maximum 80 °C rise at a 40 °C ambient condition under normal operation when operating, at the defined load point, at all speeds within the stated operating range when fed from a converter. In a variable torque load application, motors may exceed 80 °C rise at maximum speed due to the maximum load requirement along with the additional losses due to the harmonics from the converter. The motor temperature shall still not exceed 95 °C temperature rise or exceed the specified temperature class (T3, T4, etc.) on any internal or external surface depending on the protection type of the motor (Ex eb, Ex ec, Ex db, etc.). See more detailed requirement in IEC 60079 series of standards.

   NOTE For Ex eb motors the limiting temperature is 130 °C by resistance method for motors with class 155 (F) insulation system, refer to IEC 60079 series.

b) The operating load should not exceed the base nameplate power rating of the motor.

c) The motor should be operated at or below the maximum nameplate speed.

d) The shaft load profile should be variable torque, as found in centrifugal loads where per unit torque is approximately proportional to the square of the per unit speed.

   Constant torque load profiles are considered an unusual service condition since it may cause motors to overheat at lower speeds. Manufacturers may provide a speed range on the nameplate for which constant torque is acceptable. This is per an agreement between the manufacturer and the end user. Take care to stay within the allowed temperature rise or maximum allowed surface temperature throughout the speed range.

e) The maximum ambient temperature should not exceed 40 °C. The minimum ambient should not be lower than: -20 °C for grease lubrication, +0 °C for oil lubrication, or +5 °C for water cooling. Higher or lower temperatures are considered an unusual service condition but may be agreed on by the manufacturer and end user.

f) The maximum altitude should not exceed 1000 m above mean sea level.

g) The motor (and drive) should be designed for continuous (S1) duty operation.

h) Induction motors should have a torque-speed characteristic at rated load corresponding to a “low slip” design.

i) The maximum exposed surface temperature of any portion of the machine or its accessories should not exceed 200 °C or the relevant auto-ignition temperature – whichever is lower – when operated on a converter.

j) The voltage/frequency ratio during continuous operation should be within ±10 % or higher of the nameplate base rating depending on the rating.

k) The motor should be manufactured to meet the applicable requirements of IEC 60034-1.

l) For converter-fed applications, the current setting should be 100 % of the rated motor current; overload device settings should be set no higher than 115 % of rated nameplate current.

Motors outside the above range should be per agreement of manufacturer and end-user.

18.13 Unusual service conditions

18.13.1 Converter capable motors

Shall be suitable unless otherwise specified for the site conditions defined in IEC 60034-1:2022, Clause 6 during operation, at standstill, in storage or in transport.

18.13.2 Unusual converter-fed applications

Where any one or more conditions differ from the complete list outlined in 18.12.1, the converter capable motor is deemed to be in an unusual service condition. These situations require special consideration by the user, application engineer, and both motor and drive manufacturers to fully understand the issues and develop a solution that will not be a source of ignition.

19 Additional considerations for synchronous reluctance electrical machine fed by voltage source converters

19.1 System characteristics

The benefits of a PDS consisting of a voltage source converter and a synchronous reluctance electrical machine instead of an induction electrical machine are:

- losses in the electrical machine might be lower. For system efficiency, a review the losses in the converter shall be taken into account;
- reduced electrical machine size, compared with an induction electrical machine of the same rating;
- no winding losses in the rotor gives lower bearing temperatures compared to an induction electrical machine;
- simpler cooling arrangements of the electrical machine, due to minimal rotor losses.

19.2 Losses and their effects

The statements of Clause 5 remain valid.

19.3 Noise, vibration and torsional oscillation

The statement of Clause 6 remains valid.

19.4 Electrical machine insulation electrical stresses

The statement of Clause 7 remain valid.

19.5 Bearing currents

The statement of Clause 8 remain valid.

19.6 Particular aspects of synchronous reluctance electrical machines

- Power factor is generally not as good as with induction electrical machines.
- Operation in field weakening range requires special measures to ensure that needed torque is available.

Annex A
(informative)

Converter characteristics

A.1 Converter control types

A.1.1 General

A.1.1.1 General remarks

There are various converter control types: scalar, vector (sensorless or feedback), direct flux and electrical machine torque control, etc. Each type has different characteristics, which are described in A.1.1.2 to A.1.1.4.

A.1.1.2 Scalar control

Scalar control is the original concept in a V/Hz converter. In such a converter, the output voltage is controlled according to the output frequency. Figure 3 shows examples of the ways in which this may be done.

With converter output voltage proportional to frequency, the electrical machine is operating with approximately constant flux even without feedback signals.

Voltage boost (a fixed voltage which is added to the converter output voltage), conventional IR (stator winding resistance voltage drop) compensation, or advanced dynamic voltage compensation are commonly used options to improve starting and operating performance in the low speed region.

Voltage boost has more effect at low speeds when the electrical machine voltage is low, and care should be taken to ensure that the boost voltage is not so high that the electrical machine saturates.

IR compensation, where at light loads the amount of boost voltage is proportional to the amount of current in the electrical machine, is an improvement. Many scalar controls use special algorithms to dynamically compensate for the voltage drop caused by electrical machine stator resistance and inductance. This provides even better starting and operating performance in the low speed region, and, by using additional electrical machine voltage and current feedback signals, such controls can generate torque values close to vector control even at lower frequency regions.

Scalar control is generally applied where fast response to torque or speed commands is not required and it is particularly useful if multiple electrical machines are to be supplied from a single converter.

A.1.1.3 Vector control

An AC vector controlled converter essentially decouples the components of the electrical machine current producing the magnetizing flux and the torque, in order to control them separately.

This decoupling is achieved by calculation of the electrical machine characteristics using an equivalent circuit (mathematical model) with or without speed feedback signals.

According to the level of performance required, different approaches may be taken for this equivalent circuit calculation. In addition, a speed feedback (sensor) signal may further improve the performance.

Vector control is usually applied when fast torque and speed responses are required.

A.1.1.4 Direct flux and electrical machine torque control

A direct flux and electrical machine torque-controlled converter has a hysteresis (also known as sliding mode) control type, which adjusts the flux and the torque of the electrical machine by mathematical model calculation of the electrical machine, with or without speed feedback signals.

In this control type, there is no modulator, every switching transition of each converter power semiconductor being considered separately. In addition, a speed feedback (sensor) signal may further improve the performance.

Direct flux and electrical machine torque control is usually applied when fast torque and speed responses are required.

A.1.2 Converter type considerations

All three types of control can be used for constant torque applications, as well as for applications where the torque increases with speed (for example, centrifugal pumps or fans). However, when selecting a converter, each aspect of the performance requirement should be considered to ensure optimal operation.

In general, the following aspects should be noted:

- using scalar control, it is possible to operate electrical machines of different ratings in parallel with one converter (multi-machine operation);
- scalar control is typically insufficient for dedicated low speed load requirements (below approximately 10 % of corner point speed), although the low-speed performance can be improved by applying dynamic voltage compensation;
- the steady-state torque capability of scalar control can be made equivalent to the sensorless vector control by applying dynamic voltage compensation;
- the most significant difference between scalar control and vector or direct flux and electrical machine torque control is the dynamic response;
- vector or direct flux and electrical machine torque control may be required if one or more of the following characteristics are needed:
  - operation around zero speed;
  - precise torque control;
  - high peak torque at low speed;
- using vector control or direct flux and electrical machine torque control, multi-electrical machine operation can be realized with or without speed feedback, provided that electrical machines of the same rating are used;
- the characteristics of vector control and those of direct flux and electrical machine torque control are almost equivalent, because both use mathematical model calculations of the electrical machine with or without flux or speed sensors.

Further details are available in IEC 61800-2.

A.2 Converter output voltage generation (for voltage source converters)

A.2.1 Pulse width modulation (PWM)

PWM covers those schemes of output voltage generation where the transition switching commands of the converter are generated from a "carrier-frequency" synchronized controller (the "modulator").

The modulator controls the converter output switching pattern in such a way that the output voltage is equal to the desired reference value.

NOTE The output voltage is understood as an average value for times related to the switching frequency and an instantaneous value for times related to the fundamental output frequency of the converter.

The carrier frequency may optionally be synchronized to line or to output frequency. It may be selected to reduce losses, current ripple or generated noise, and it may be kept fluctuating ("wobbling" or "random" PWM) to distribute the harmonic spectra of the output voltage over a wide range.

Additionally, special control techniques may be used to optimize the current waveform or spectrum, for example to achieve minimum current peaks or to eliminate certain harmonics.

A.2.2 Hysteresis (sliding mode)

Hysteresis covers those schemes of output voltage generation where the transition switching commands of the converter are generated from a "carrierless" (and therefore unsynchronized) controller. Transition switching occurs as soon as a certain difference is exceeded between an actual and a reference value of a control parameter.

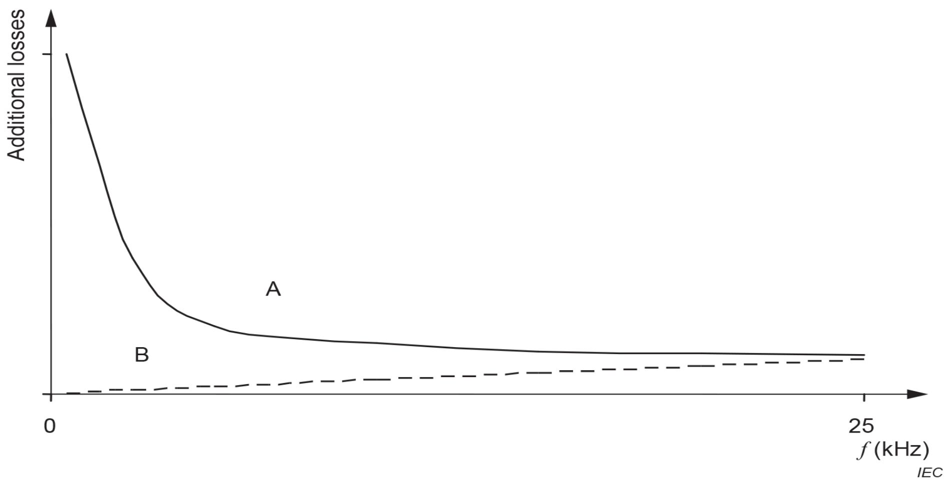
Hysteresis switching can be used with several control parameters: voltage, current, flux or torque, depending on the type of control.

A.2.3 Influence of switching frequency

The converter output switching frequency will affect the losses (in the electrical machine and in the converter), acoustic noise and torque ripple of the overall PDS. It is not possible to provide precise data on these effects, but they are shown in a general manner by Figure A.1, Figure A.2 and Figure A.3. These figures are for illustration only, and it is not intended that comparative calculations should be made from them.

NOTE 1 In Figure A.1, the vertical scales for the electrical machine losses and converter losses are not the same.

NOTE 2 For modulation schemes which do not use fixed carrier frequencies, the expression "switching frequency" means the average number of switching pulses per second.



Key

A Electrical machine losses

B Converter losses

Figure A.1 – Effects of switching frequency on electrical machine and converter losses

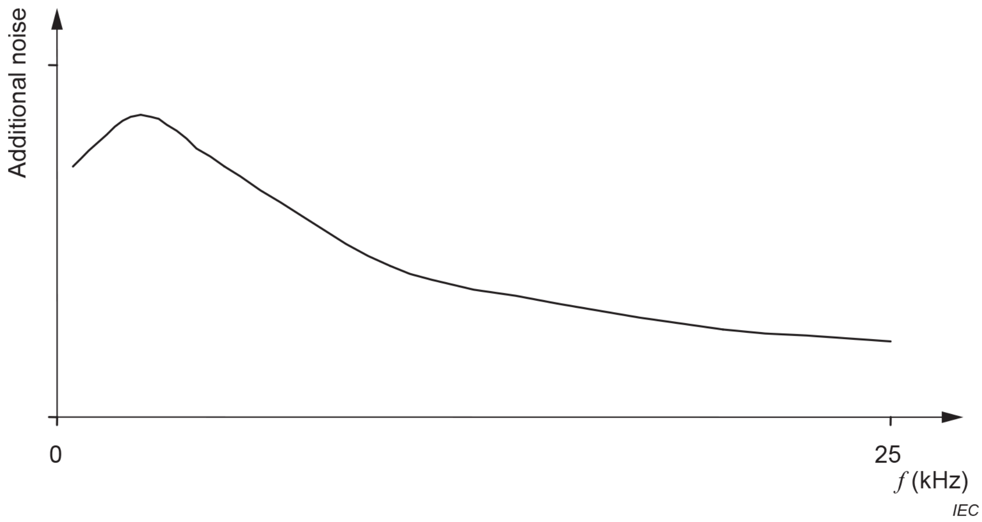
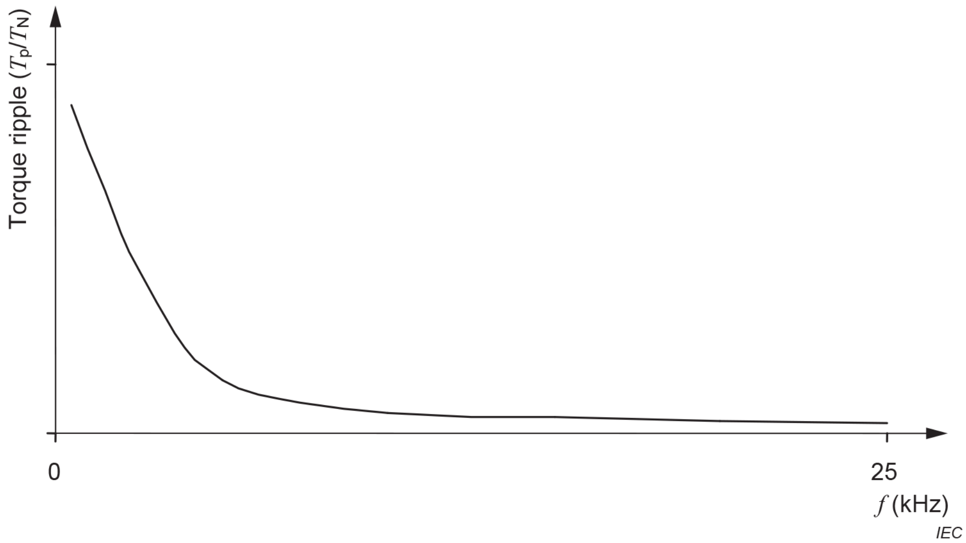


Figure A.2 – Effects of switching frequency on acoustic noise



Key

T_p Peak value of the pulsating torque

T_N Rated torque

Figure A.3 – Effects of switching frequency on torque ripple

A.2.4 Multi-level converters

In the two-level converter schemes described above, the output voltage is generated by switching between the positive and negative levels of the d.c. bus voltage.

Multi-level converter*s* offer intermediate voltage potentials for switching, and therefore the "harmonic" frequency spectra are significantly reduced in amplitude and shifted to higher frequencies.

NOTE Since multi-level converter*s* require more switching semiconductors, they are more common for high voltage applications (see IEC 61800-2).

A.2.5 Parallel converter operation

Where the converter consists of more than one inverter bridge working in parallel, it is often possible to design the electrical machine with the same number of parallel branches of the three-phase winding and connect each inverter bridge to a different winding branch.

Where voltage impressing converter*s* contain significant harmonics of the fundamental, it is recommended that the output voltages of the inverter bridges should not be shifted in phase against each other, nor should the winding systems be shifted by a circumferential angle different from 0° or 360°/p, in order to prevent the generation of large harmonic currents.

For hysteresis controlled converter*s*, winding systems mechanically shifted by 30°/p and supplied with voltages having 30° phase shift can be used.

Annex B
(informative)

Output characteristics of 2 level voltage source converter spectra

The converter output voltage waveform, and therefore the output voltage spectrum, differs according to the method of converter output voltage generation. Typical waveform is displayed in Figure B.1. Examples of the frequency components at the outputs of a converter with constant frequency (about 2,5 kHz) PWM switching and one with hysteresis switching (about 2,2 kHz average frequency) are shown in Figure B.2.

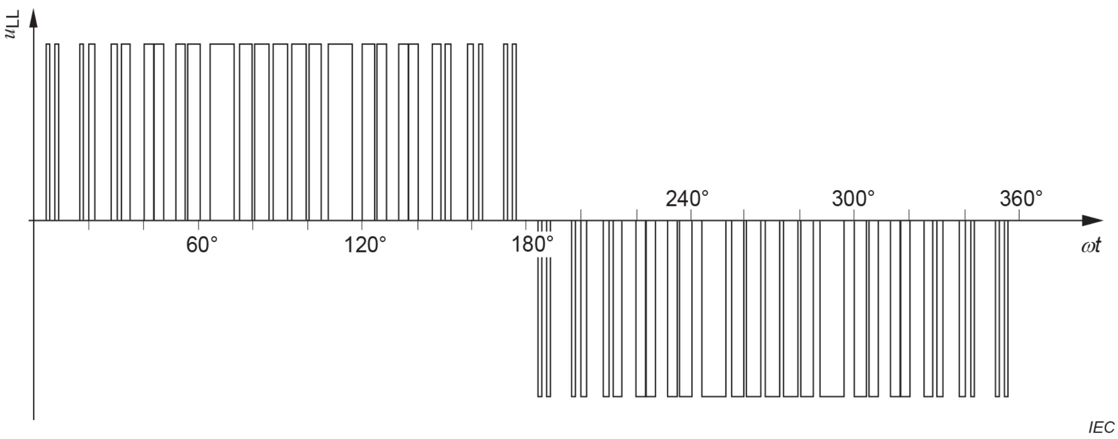


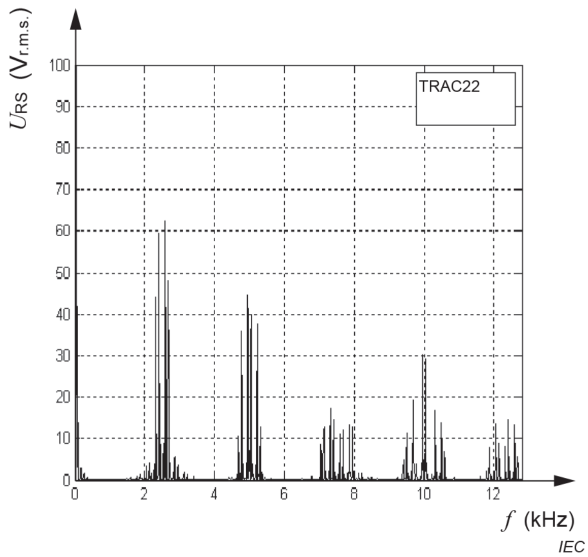
Figure B.1 – Waveform of line-to-line voltage U_{LL} for voltage source converter supply with switching frequency f_s = 30 × f_1 (example)

Converter*s* using carrier modulation, together with synchronized and asynchronous pulse patterns, as applied in many cases, produce the frequencies:

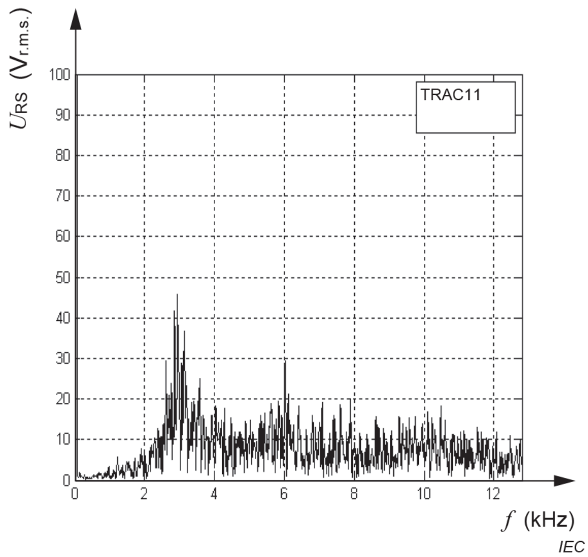
$$f = k_s \times f_s \pm k_1 \times f_1$$

where k_s = 1, 2, 3, etc., and k_1 = 1, 2, 4, 5, 7, etc., are multiplying factors of the switching frequency f_s and of the operating frequency f_1, respectively. The formula is valid also in the case of converter*s* with space-vector modulation.

Converter*s* with carrierless modulation, where no pre-determined switching frequency is existent, are also in practical use. In this case, the frequency spectrum of the output voltage is characterised by broadband random noise without spikes at specific frequencies.



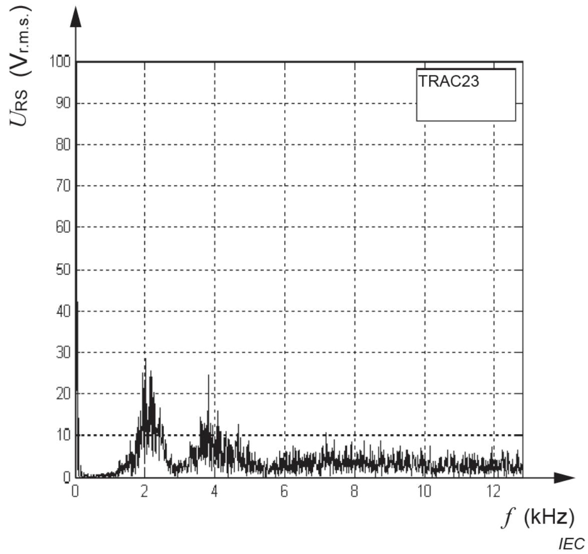
a) **Constant frequency PWM control**



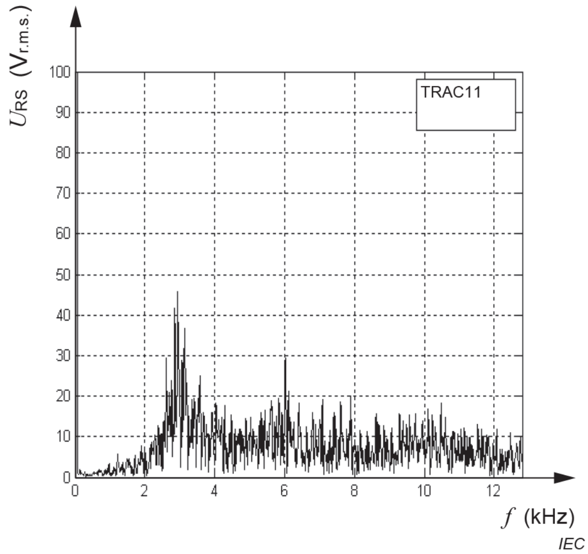
b) **Hysteresis control**

Figure B.2 – Typical output voltage frequency spectra for a constant frequency PWM control versus hysteresis control

Figure B.3 compares a typical spectrum of a random frequency (about 2,2 kHz average) PWM converter with that of a hysteresis switching converter.



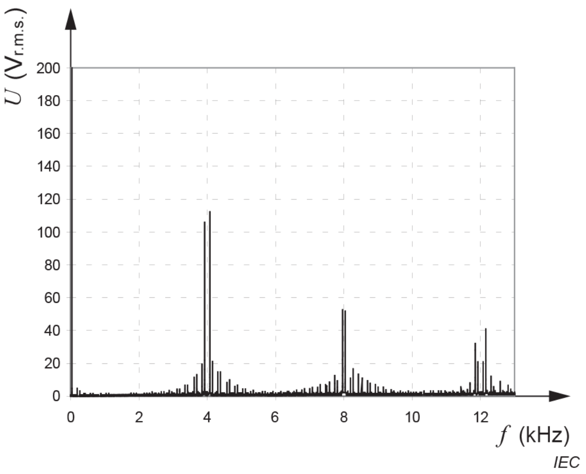
a) **Random PWM control**



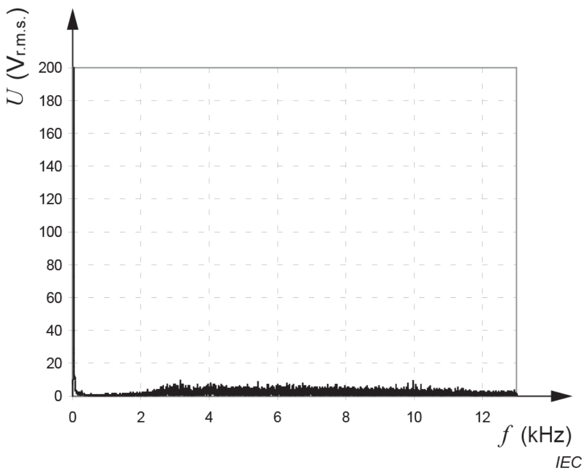
b) **Hysteresis control**

Figure B.3 – Typical output voltage frequency spectra for random frequency PWM versus hysteresis control

Figure B.4 shows typical spectra of a) a two-phase modulated converter at 4 kHz carrier, average frequency about 2,7 kHz and b) a converter with hysteresis modulation and direct torque control at 2,7 kHz average frequency.



a) **4 kHz carrier with two-phase modulation, 2,7 kHz average**

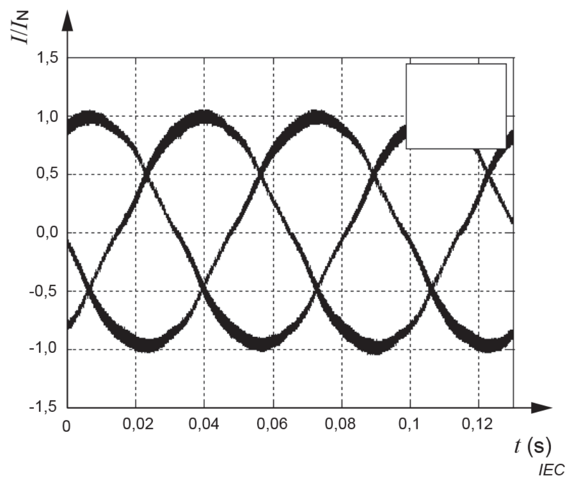


b) **Hysteresis modulation, direct torque control, 2,7 kHz average**

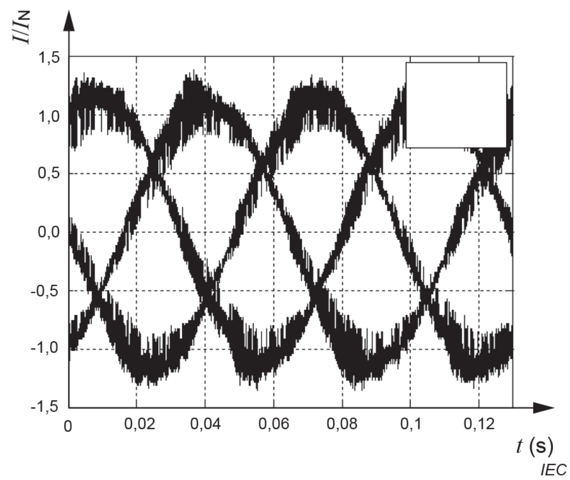
Figure B.4 – Typical output voltage frequency spectra for a two-phase modulated control versus hysteresis modulation

In all cases, the output frequency to the electrical machine was about 40 Hz, and the electrical machine load characteristics were kept constant. The frequency components of hysteresis or random frequency PWM switching are generally lower in maximum amplitude than those of constant frequency PWM switching or two-phase modulation, but are distributed more widely over the frequency range.

Figure B.5 shows typical (normalized) electrical machine current time characteristics of the two converter*s* having the spectra illustrated in Figure B.2 . In this case, the output (rotational) frequency was about 10 Hz.



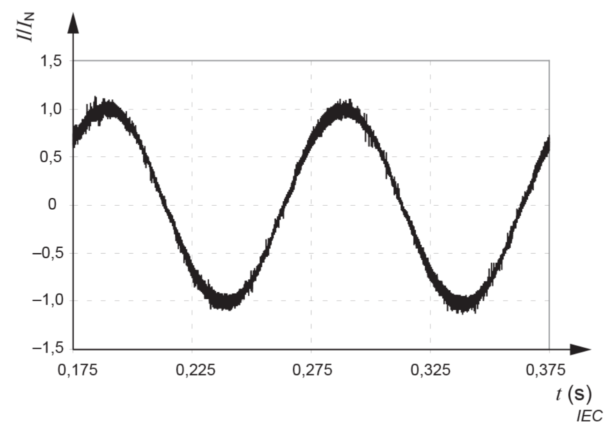
a) **Constant frequency PWM control**



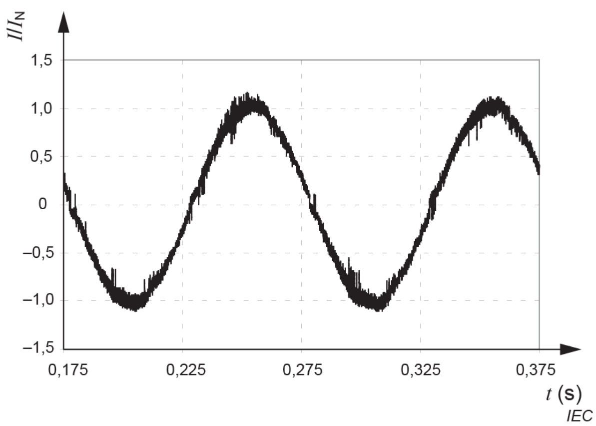
b) **Hysteresis control**

Figure B.5 – Typical time characteristics of electrical machine current for a Constant frequency PWM control versus hysteresis control

Figure B.6 shows the time characteristics of the output of the two converter*s* having the spectra illustrated in Figure B.4. Again, the output (rotational) frequency was about 10 Hz.



a) 4 kHz carrier with two-phase modulation, 2,7 kHz average



b) Hysteresis modulation, direct torque control, 2,7 kHz average

Figure B.6 – Typical time characteristics of electrical machine current for a two-phase modulated control versus hysteresis modulation

Figure B.1 to Figure B.6 are for illustration only. They should not be used to qualify or disqualify the methods of voltage generation as such. All methods of output voltage generation can be optimized in special ways to balance advantages and disadvantages in the application.

Annex C
(informative)

Voltages to be expected at the power interface between converter and electrical machine

In practice, the voltage to be expected at the terminals of an electrical machine fed from a converter – especially of a voltage source converter – differs from the ideal theoretical pulse patterns as given in Figure B.1 due to transient high frequency effects. Figure C.1 shows a typical example. These effects are significantly influenced by various parameters such as the cable length and cable type between electrical machine and converter, the details of the grounding system used, the parasitic earth capacitance of the motor, the use of output filters, the rise-time of the voltage pulses, etc. The latter ones and the associated voltage changes at the inverter output and at the motor terminals are not directly comparable. The differences are mainly caused by the above described high-frequency characteristics of the drive components being used. Thus, a distinction shall be made between the slopes directly at the power semiconductors, the values at the inverter output and those at the motor terminals. In principle, the specified values for the voltage-rise-times in the area of the inverter can be higher than the permissible values at the motor terminals.

As described in 7.3 short voltage-rise-times at the electrical machine terminals can possibly lead to early dielectric breakdowns turn-to-turn. The risk of such failures can be minimized by using enameled wires with an appropriate dielectric strength and resin filling. The relevant field experience provides also the proof that despite the above-mentioned differences in the steepness values converter motor, a reliable operation without harming the motor insulation system is provided.

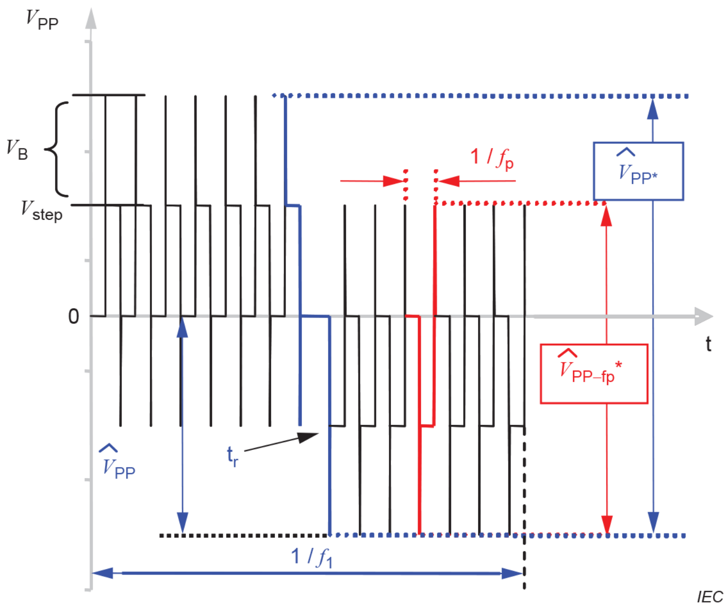


Figure C.1 – Example of typical voltage curves and parameters of a two level inverter versus time at the electrical machine terminals (phase to phase voltage; taken from IEC TS 61800-8)

It is impossible to specify general limits for the maximum voltage stress to be expected. Instead, it is necessary to determine the voltage stress for each application individually based on IEC TS 61800-8, which provides all required information.

NOTE IEC TS 61800-8 uses different symbols for quantities from IEC 60034. E.g., V instead of U is used for voltages, and the line-to-line voltage is addressed as V_{pp} instead of U_{LL}.

In order to identify the maximum values to be expected for the line-to-line and line-to-ground voltage at the electrical machine terminals and other values that influence the proper choice of the insulation system for the stator winding, the following information is required:

a) Line section: Nominal voltage and type (TN, TT, IT) of supply system.
b) Input converter (rectifier): Single phase, three phase diode or three-phase active infeed including kind of DC choke, if any.
c) Output converter (inverter): Two-level, three-level or multi-level (with floating capacitor or multi DC-link).
d) Filter section (if any): HF common-mode, du/dt, output choke or sine wave.
e) Cabling section: Length and characteristic parameters (capacity and inductance) per metre.

IEC TS 61800-8 provides the influence of these options on the maximum voltages in the form of tables with characteristic amplifying factors. The calculation scheme shall be demonstrated by two typical examples showing the significant dependency of the voltages on the PDS arrangement. All table, formula and subclause numbers refer to IEC TS 61800-8:2010.

Example 1: 3 kW electrical machine for 400 *U* fed by a two-level converter with diode rectifier via a 2 m cable without filter.

Line section:
TN type supply with star point grounding and 400 V nominal voltage
⇒ differential mode amplification factor (5.4, Table 1)
V_s/V_{sN} = 1,1 including 10 % line voltage tolerance
⇒ common-mode amplification factor (5.5, Table 2)
$k_{C0} = 0$

Input converter section:
Three-phase diode input converter without DC choke and without dynamic breaking
⇒ differential mode amplification factor (6.8, Table 6)
$k_{D1} = 1,35$
⇒ common-mode amplification factor (6.9, Table 7)
$k_{C1} = 0$

Output converter section:
Two-level output converter
⇒ differential mode amplification factor (7.9, Table 18)
$k_{D2} = 1$
⇒ common-mode amplification factor (7.10, Table 19)
$k_{C2} = \pm½$
⇒ dynamic parameters (7.11, Table 20)
t_{r2} = 50 ... 200 ns
f_P/f_1 = 5 ... 300

Filter section:
No filter
⇒ differential mode amplification factor (8.4, Table 21)
$k_{D3} = 1$
⇒ common-mode amplification factor (8.5, Table 22)
$k_{C3} = 1$
⇒ dynamic parameters (8.4 and 8.5, Tables 21 and 22)
$t_{r3} = t_{r2}$ = 50 ... 200 ns

Cabling and electrical machine section:
Rated electrical machine power below 3,7 kW, 2 m cable with characteristic inductance 650 nH/m, characteristic capacity 130 pF/m

⇒ propagation velocity (9.1, formula 27)
ν = 1 / sqrt(650 nH/m · 130 pF/m) = 109 m/µs

⇒ critical cable length (9.1, formula 28)
l_{cr} = ½ · 109 m/µs · (50 ... 200 ns) = 2,725 m ... 10,9 m
cable length is below critical length

⇒ reflection coefficient (9.2, Table 23)
Γ = 0,95

⇒ differential mode amplification factor (9.3, Table 24)
k_{D4} = (2 · 0,95 / 2,725 + 1) = 1,7

⇒ common-mode amplification factor (9.3, Table 24)
k_{C4} = (2 · 0,95 / 2,725 + 1) = 1,7

⇒ dynamic parameters (9.3, Table 24)
t_{r4} = (50 ... 200) ns · (2 · 0,95 / 2,725 + 1) = 85 ... 340 ns

⇒ Peak value of phase-to-ground voltage at electrical machine terminals:
$\hat{V}_{PG,Machine}$ = 1,1 · 400 *U* / 1,732 · (1,35 · 1 · 1 · 1,7) + 1,1 · 400 *U* · (0 + 0 ± ½) · 1 · 1,7
= 583 V ± 374 V = 209 ... 957 V

⇒ Zero-to-peak value of phase-to-phase voltage at electrical machine terminals:
$\hat{U}_{PP}$ = 1,1 · 400 *U* · (1,35 · 1 · 1 · 1,7) = 1 010 *U*

Example 2: 3 kW electrical machine for 690 V fed by a two-level converter with diode rectifier and unsymmetrical DC choke via a 50 m cable without filter including dynamic breaking.

Line section:
IT type supply with 690 V nominal voltage

⇒ differential mode amplification factor (5.4, Table 1)
U_s/U_{sN} = 1,1 including 10 % line voltage tolerance

⇒ common-mode amplification factor (5.5, Table 2)
k_{C0} = 0,577

Input converter section:
Three-phase diode input converter with unsymmetrical DC choke and dynamic breaking with resistor and chopper

⇒ differential mode amplification factor (6.8, Table 6)
k_{D1} = 1,6

⇒ common-mode amplification factor (6.9, Table 7)
k_{C1} = ± 0,675

Output converter section:
Two-level output converter

⇒ differential mode amplification factor (7.9, Table 18)
k_{D2} = 1

⇒ common-mode amplification factor (7.10, Table 19)
k_{C2} = ±½

⇒ dynamic parameters (7.11, Table 20)
t_{r2} = 50 ... 200 ns
f_P/f_1 = 5 ... 300

Filter section:
No filter

⇒ differential mode amplification factor (8.4, Table 21)
k_{D3} = 1

⇒ common-mode amplification factor (8.5, Table 22)
k_{C3} = 1

⇒ dynamic parameters (8.4 and 8.5, Tables 21 and 22)
$t_{r3} = t_{r2}$ = 50 ... 200 ns

Cabling and electrical machine section:
Rated electrical machine power below 3,7 kW, 50 m cable with characteristic inductance 650 nH/m, characteristic capacity 130 pF/m

⇒ propagation velocity (9.1, formula 27)
ν = 1 / sqrt(650 nH/m · 130 pF/m) = 109 m/μs

⇒ critical cable length (9.1, formula 28)
l_{cr} = ½ · 109 m/μs · (50 ... 200 ns) = 2,725 m ... 10,9 m
cable length is above critical length

⇒ reflection coefficient (9.2, Table 23)
Γ = 0,95

⇒ differential mode amplification factor (9.3, Table 24)
k_{D4} = 1 + 0,95 = 1,95

⇒ common-mode amplification factor (9.3, Table 24)
k_{C4} = 1 + 0,95 = 1,95

⇒ dynamic parameters (9.3, Table 24)
t_{r4} = (50 ... 200) ns · (1 + 0,95) = 97,5 ... 390 ns

⇒ Peak value of phase-to-ground voltage at electrical machine terminals:
$\hat{V}_{PG,Machine}$ = 1,1 · 690 V / 1,732 · (1,6 · 1 · 1 · 1,95) + 1,1 · 690 V · (0,577 ± 0,675 ± ½) · 1 ·1,95
= (1367 V – 885 V) ... (1367 V + 2593 V) = 482 ... 3 960 V

⇒ Zero-to-peak value of phase-to-phase voltage at electrical machine terminals:
$\hat{V}_{PP}$ = 1,1 · 690 V · (1,6 · 1 · 1 · 1,95) = 2 368 V.

Annex D
(informative)

Speed and harmonic capability of converter capable induction motor

D.1 General

The following clauses identify the derating that may be required on self-cooled motors when running on a converter if the motor would run at its maximum allowed temperature at rated load and speed on a sinusoidal power supply. It is recognized that some motors may run cooler than the allowed insulation class and will not require derating or as much derating.

Derating for independent cooled motors is not covered here as cooling is not as dependent on speed.

D.2 Harmonic capability of converter capable motors

For a motor to be defined as being converter capable, it shall be able to stay within its rated thermal insulation class despite increased losses due to harmonics voltages and currents delivered to the motor from a voltage source inverter (VSI). The expected increase in losses and temperature rise of the motor could be range from 15 % to 25 % as compared to a clean operation from a pure sinusoidal input.

AC motors rated for use on a power supply of fixed frequency (whether with a local AC generator or via a supply network) shall be suitable for operation on a supply voltage having a harmonic voltage factor (HVF) not exceeding: 0,03 for design N motors with no increase in temperature rise. A thermal class 130 (B) rise motor shall be capable of running within thermal class 155 (F) insulation levels when running operating on any drive with harmonics in the output voltage that result in an increase of losses up the 15 % to 25 % that could be expected. The motor shall stay in the thermal class 155 (F) temperature range at speeds down to 80 %. of rated speed. If it is desired to maintain the temperature rise that would be achieved on a sinusoidal input and with up to 0,03 HVF, the motor should be de-rated per the following curve in Figure D.1.

The harmonic voltage factor (HVF) is defined as follows:

$$\sqrt{\sum_{n=5}^{n=\infty} \frac{U_n^2}{n}}$$

where

n is the order of odd harmonic, not including those divisible by three;

U_n is the the per-unit magnitude of the voltage at the n^{th} harmonic frequency.

EXAMPLE: With per-unit voltages of 0,10, 0,07, 0045, and 0,036 occurring at the 5, 7, 11, and 13th harmonics, respectively, the value of the HVF is:

$$\sqrt{\frac{0,10^2}{5} + \frac{0,07^2}{7} + \frac{0,045^2}{11} + \frac{0,36^2}{13}} = 0{,}0546$$

For design N, NE, NEY, H, HE, and HEY motors defined in IEC 60034-12 and larger induction motors when the HVF level is greater than 0,03 the motor should be derated per Figure D.1.

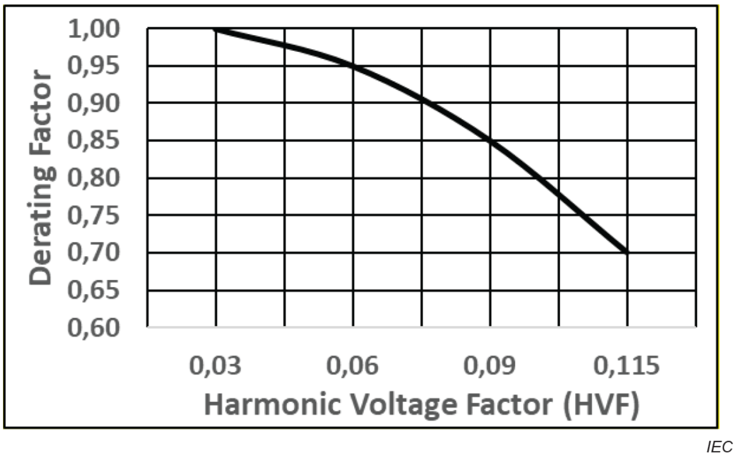


Figure D.1 – Derating curve for harmonic voltages

In this example derating would be to approximately 0,96 per unit of the motor rating.

D.3 Speed capability and derating in variable torque application

When driving a variable torque (VT) Load, where the load is maximum at the corner point as defined in Figure 1 the motor will run it's hottest near to the top-rated operating speed (corner point) within the VT range. It will run cooler as the operating speed goes down. For a thermal class 130 (B) rise rated motor with sinusoidal input voltage, the motor could run on a converter with a total winding temperature as high as 145 °C within the range of rated speed and frequency range. Motor may run at the elevated temperature to minus 15 % from rated frequency (corner frequency). From minus 15 % to ¼ rated frequency motor should run within the class 130 (B) rise. For example, a 50 Hz motor rated 130 (B) rise on a Sine wave the motor will run < 130 (B) rise 12,5 Hz to 42,5 Hz and < F rise 42,5 Hz to 50 Hz.

D.4 Speed capability and derating in a constant torque application

When driving a constant torque application, a thermal class 130 (B) Sinusoidal rated motor will stay with in thermal class 155 (F) insulation temperature rise within when operated between rated frequency down to rated frequency minus 20 %. Below minus 20 % of rated frequency, the motor shall be derated per Figure D.2 to stay within the class 155 (F) insulation class.

Induction motors to be operated in adjustable-speed drive applications should also be derated as a result of the effect of additional losses introduced by harmonics generated by the control. The torque available from the motor for continuous operation is usually lower than on a sinusoidal voltage source. The reduction results from the additional temperature rise due to harmonic losses and also from the voltage-frequency characteristics of some controls.

The rise in temperature at any load-speed point depends on the individual motor design, the type of cooling, the effect of the reduction in speed on the cooling, the voltage applied to the motor, and the characteristics of the control. When determining the derating factor, the thermal reserve of the particular motor is important. Taking all of these matters into account, the derating factor at rated frequency ranges from 0 % to 20 %.

Figure D.2 shows examples of a derating curve for a typical motor that are running close to their design limit at rated frequency. If a motor has additional thermal reserve to the allowed temperature class, such as may be seen on some premium efficiency motors or non-ventilated motors, less derating will be required. For example, if the motor has a class 130 (B) temperature rise but utilizes thermal class 155 (F) insulation and the full insulation class is permitted to be utilized then no derating may be required at rated frequency. Torque derating may still be required at reduced speed.

Other motors with different thermal reserve, different methods of cooling (self-circulation cooling or independent cooling) and used with other types of controls will have different derating curves or may also require little to no derating. The curves shown here assume for example a class 130 (B) rise motor runs at its temperature limit on a sinusoidal power supply.

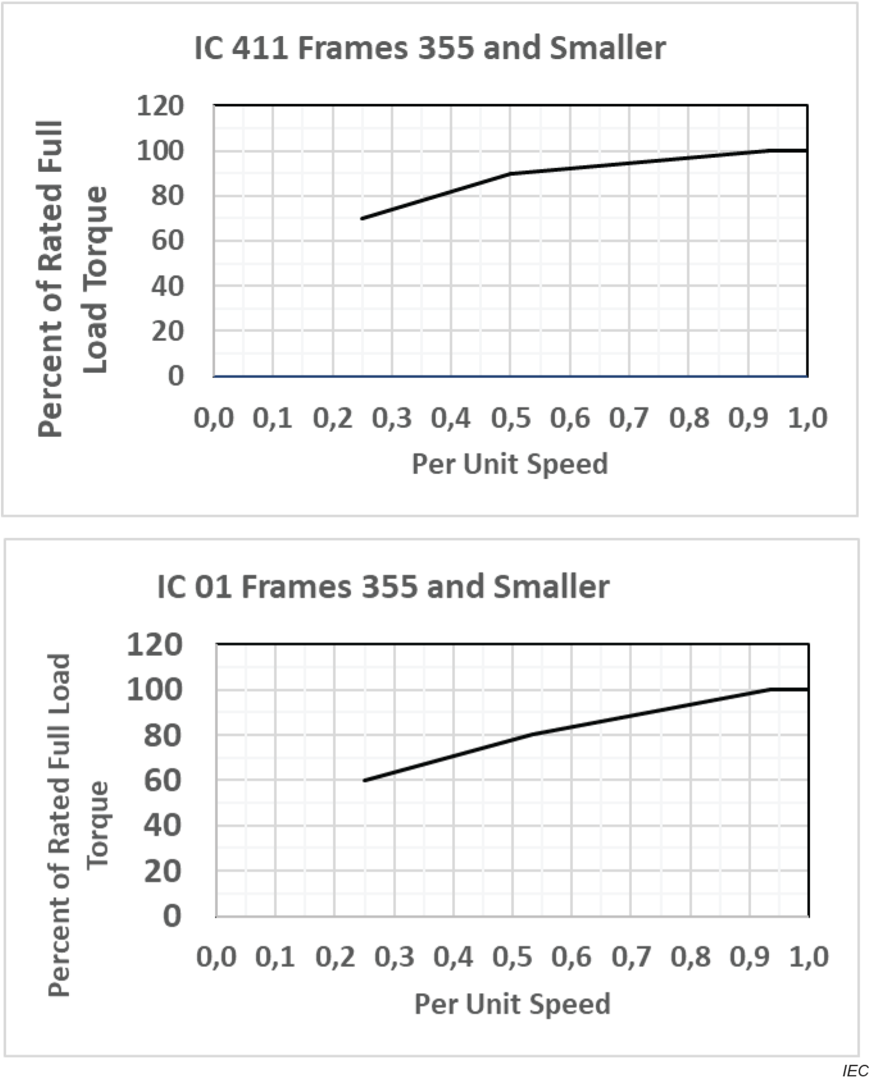


Figure D.2 – Torque capability at reduced speeds due to the effects of reduced cooling (applyies to 50 Hz or 60 Hz design N)

All curves are based on a sinusoidal wave shape, rated air-gap flux. Additional derating for harmonic voltages should be applied as a multiplier to the above limits.

a) The curves may also apply to class 130 (B) 80 K if permitted to run at the next insulation class of thermal class 155 (F) 105 K rise by resistance with an additional 15 % to 25 % harmonics losses.

b) All curves are based on non-injurious heating which may exceed rated temperature rise.

c) Curves are applicable only to frame sizes and design types indicated. For larger frames or other design types consult the motor manufacturer.

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NEMA MG 1: *Motors and Generators*, National Electrical Manufacturers Association, Rosslyn, VA

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