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Rotating electrical machines –

Part 25:
Guide for the design and performance of cage induction motors specifically designed for converter supply

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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ROTATING ELECTRICAL MACHINES –

Part 25: Guide for the design and performance of cage induction motors specifically designed for converter supply

FOREWORD

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- The subject is still under technical development or where, for any other reason, there is the future but no immediate possibility of an agreement on an International Standard.

Technical specifications are subject to review within three years of publication to decide whether they can be transformed into International Standards.

IEC 60034-25, which is a technical specification, has been prepared by IEC technical committee 2: Rotating machinery.

The text of this technical specification is based on the following documents:

Enquiry draft	Report on voting
2/1271/DTR	2/1288/RVC

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

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

The committee has decided that the contents of this publication will remain unchanged until 2007. At this date, the publication will be

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- withdrawn;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

A bilingual edition of this Technical Specification may be issued at a later date.

INTRODUCTION

This introduction is intended to explain the aim of this part of IEC 60034.

Motor categories

There are 2 categories of cage induction motors, which can be applied in variable speed electric drive systems.

- Standard cage induction motors, designed for general purpose application. The design and performance of these motors are optimized for operation on a fixed-frequency sinusoidal supply. Nevertheless they are generally also appropriate for use in variable speed drive systems.

  Guidance on this field of application is given in IEC 60034-17.
- Cage induction motors specifically designed for converter operation. The design and construction of such motors may be based on standard motors with standardized frame sizes and dimensions, but with modifications for converter operation.

  This category is covered by this part of IEC 60034, and it is recommended that the motor be marked with a reference to this part of IEC 60034.

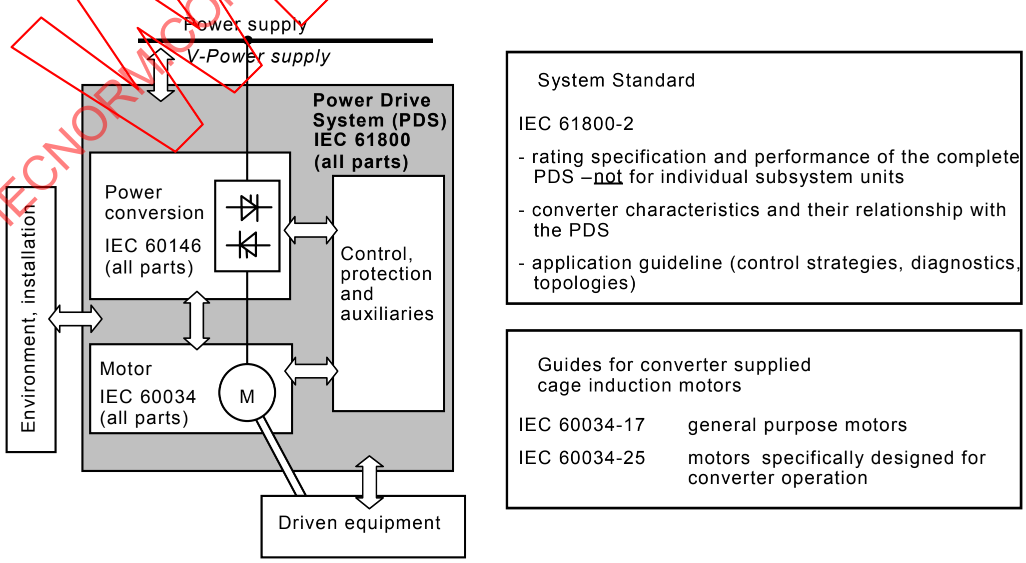
Motors for converter supplies greater than 1 000 V, or for converters other than voltage source, will be considered in later editions of this part of IEC 60034.

Incorporation of the motor into the power drive system

Figure 1 illustrates the Power Drive System (PDS). A PDS consists of a motor and a Complete Drive Module (CDM). It does not include the equipment driven by the motor. The CDM consists of a Basic Drive Module (BDM) and its possible extensions such as the feeding section or some auxiliaries (for example ventilation). The BDM contains converter, control and self-protection functions. The rating and performance of the complete PDS is covered in general by IEC 61800-2.

NOTE Figure 1 of IEC 61800-2 provides further details of the structure of a PDS.

The motor itself and additional specific requirements for its proper incorporation into the PDS are covered by the IEC 60034 series.



IEC 445/04

Figure 1 – Component parts of a PDS

ROTATING ELECTRICAL MACHINES –

Part 25: Guide for the design and performance of cage induction motors specifically designed for converter supply

1 Scope

This part of IEC 60034 describes the design features and performance characteristics of polyphase cage induction motors specifically designed for use on voltage source converter supplies up to 1 000 V. It also specifies the interface parameters and interactions between the motor and the converter including installation guidance as part of a power drive system.

NOTE 1 For motors operating in potentially explosive atmospheres, additional requirements as described in the IEC 60079 series apply.

NOTE 2 This technical report is not primarily concerned with safety. However, some of its recommendations may have implications for safety, which should be considered as necessary.

NOTE 3 Where a converter manufacturer provides specific installation recommendations, they should take precedence over the recommendations of this technical report.

2 Normative references

The following referenced documents are indispensable for the application 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, *Rotating electrical machines – Part 1: Rating and performance*

IEC 60034-2:1972, *Rotating electrical machines – Part 2: Methods for determining losses and efficiency of rotating electrical machinery from tests (excluding machines for traction vehicles)*
Amendment 1 (1995)
Amendment 2 (1996)

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

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

IEC 60034-14, *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 60034-17, *Rotating electrical machines – Part 17: Cage induction motors when fed from converters – Application guide*

IEC 61800-2, *Adjustable speed electrical power drive systems – Part 2: General requirements – Rating specifications for low voltage adjustable frequency a.c. power drive systems*

IEC 61800-3, *Adjustable speed electrical power drive systems – Part 3: EMC product standard including specific test methods*

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

3 Terms and definitions

For the purposes of this part of IEC 60034, the following terms and definitions apply.

3.1
bonding
electrical connection of metallic parts of an installation together and to ground (earth)

NOTE For the purposes of this part of IEC 60034, this definition combines elements of IEV 195-01-10 (equipotential bonding) and IEV 195-01-16 (functional equipotential bonding).

3.2
converter
operating 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

[IEC 61800-2, 2.2.1]

NOTE This definition is taken from IEC 61800-2, and for the purposes of this part of IEC 60034 embraces the terms Complete Drive Module (CDM) and Basic Drive Module (BDM) as used in the IEC 61800 series.

3.3
EMC (electromagnetic compatibility)
ability of an equipment or system to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances to anything in that environment

[IEV 161-01-07]

3.4
field weakening
motor operating mode where motor flux is less than the flux corresponding to the motor rating

3.5
peak rise time
time interval between the 10 % and 90 % points of the zero to peak voltage (see Figure 14)

3.6
Power Drive System
PDS
system consisting of power equipment (composed of converter section, AC motor 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.)

3.7
protective earthing
PE
earthing a point or points in a system or in an installation or in equipment for the purposes of electrical safety

[IEV 195-01-11]

3.8
skip band
small band of operating frequencies where steady-state operation of the PDS is inhibited

3.9
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

[IEV 161-04-15]

4 System characteristics

4.1 General

Although the steps in specifying motor 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.

4.2 System information

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

- The power or torque requirements at various speeds.
- The desired speed range of the load and motor.
- 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 reflected at the motor, load torque during starting).
- Whether the application is a continuous process or a duty cycle of starts, stops, and speed changes.
- A general description of the type of application including the environment in which the drive system components will operate.
- A description of additional functionality that may not be met with the motor and converter only (for example: motor temperature monitoring, ability to bypass the converter if necessary, special sequencing circuits or speed reference signals to control the drive system).
- 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

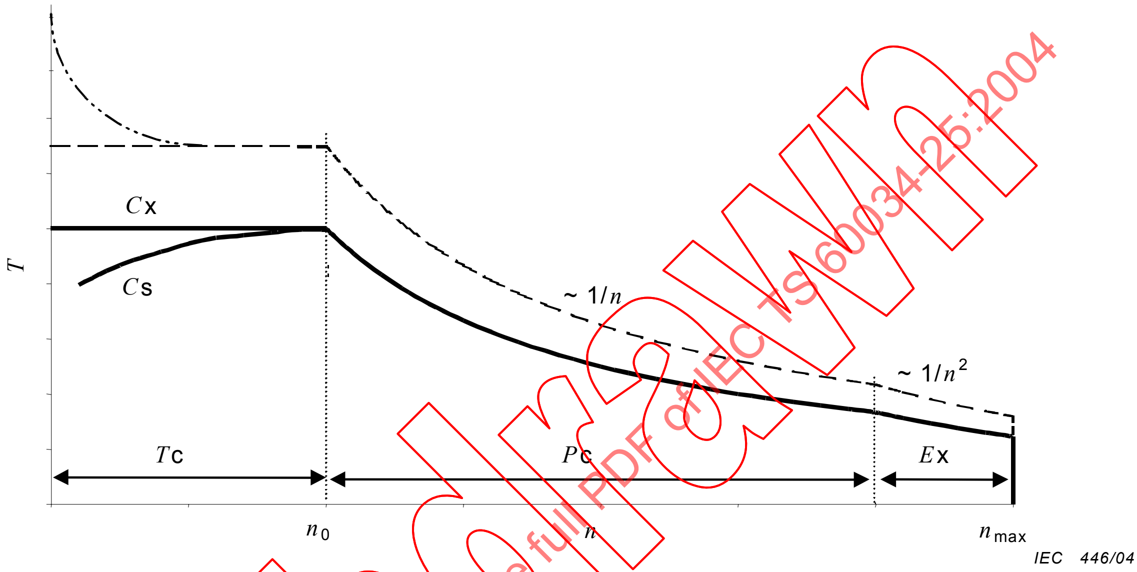
4.3.1 General

The typical torque/speed characteristics of converter-fed cage induction motors, the significant influencing factors and their consequences are shown in Figure 2, Figure 3 and Figure 4. Depending on the performance requirements of the power drive systems, different motor designs are possible for an adaptation of the individual limiting values.

NOTE Figure 2 to Figure 4 do not show the possible skip bands (see 4.3.5).

4.3.2 Torque/speed capability

Figure 2 shows the torque/speed capability of converter-fed cage induction motors. The maximum available torque is limited by the rating of the motor and by the current limitation of the converter. Above the field-weakening frequency f_0 and speed n_0 the motor can operate with constant power with a torque proportional to $1/n$. 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). The maximum speed n_{max} is limited by the mechanical strength and stability of the rotor, by the speed capability of the bearing system, and by other mechanical parameters.



Key

——— continuous operation

-------- short-time operation

—-—-- starting boost

*T*c – constant torque range

*P*c – constant power range

*E*x – extended range

*C*x – separate cooling

*C*s – self-cooling

Figure 2 – Torque/speed capability

Figure 3 shows the corresponding converter output current (I) capability.

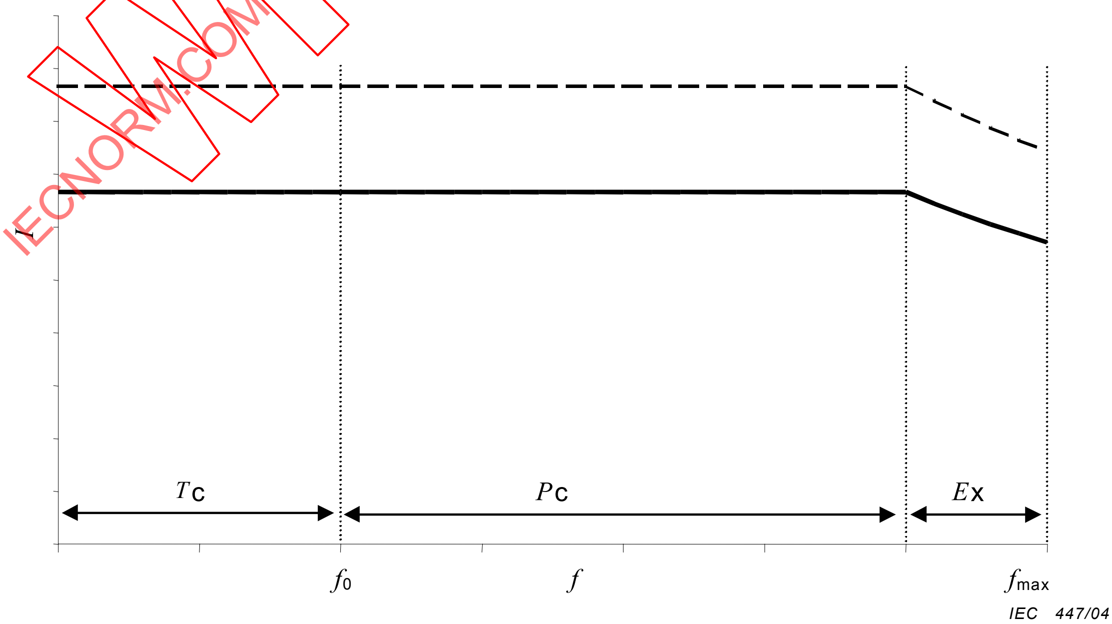
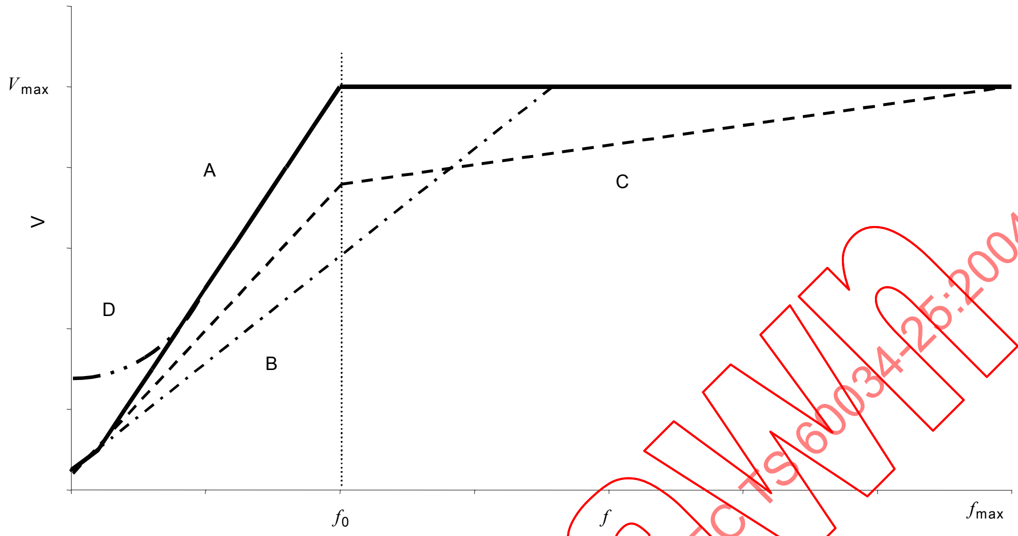


Figure 3 – Converter output current

4.3.3 Voltage/speed characteristics

The converter output voltage (V) can be varied with speed in several ways, as shown in Figure 4.



Key

A The voltage increases with speed, and the maximum converter output voltage V_{max} is achieved at the field-weakening frequency f_0.

B The voltage increases with speed, and the maximum converter output voltage V_{max} is achieved above f_0. This provides an extended speed range at constant flux (constant torque), but the available torque is reduced in this speed range.

C The voltage increases with speed up to f_0, and then increases at a lower rate, the maximum converter output voltage V_{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 speeds to improve starting performance.

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

Figure 4 – Converter output 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	Motor	Converter and motor
Breakaway	Maximum flux capability	Maximum current
Constant flux	Cooling (I^2R losses due to current variations)	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 Resonant speed bands

The speed range of a converter-fed motor may include speeds that can excite resonances in parts of the motor stator, in the motor/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 motor is set to run at any speed above this resonant speed. Decreasing the acceleration time can help minimize the time spent in resonance.

4.3.6 Duty cycles

4.3.6.1 General

Duty cycle 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 motor and the converter.

- Motor heat dissipation is variable, depending on rotation speed and cooling method.
- Torque demands above motor full-load torque may be required. Operation above motor full load may be required to accelerate, handle peak loads, and even decelerate the load. Operation above motor rated current will increase motor heating. This may require a higher thermal class of insulation, a motor rated for the overload, or evaluation of the duty cycle to determine if the motor 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 motor speed. Regardless of whether the motor is generating torque to drive the application, generating power back to the converter due to the motor being driven by the load, or supplying braking torque during deceleration by applying DC current to the windings, motor 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 61800-6 provides information on load duty and current determination for the entire PDS.

4.3.6.2 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 motor very quickly. It is also possible for this load torque to be positive (against the direction of rotation of the motor) or negative (in the same direction as motor rotation).

The impact load will result in a rapid increase or decrease in current demand (from the converter). If the torque is negative, the motor 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 motor.

4.4 Converter control types

4.4.1 General

There are various converter control types: scalar, vector (sensorless or feedback), direct flux and motor torque control, etc. Each type has different characteristics, which are described in 4.4.1.1 to 4.4.1.3.

4.4.1.1 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 4 shows examples of the ways in which this may be done.

With converter output voltage proportional to frequency, the motor is operating with approximately constant flux even without speed 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 motor voltage is low, and care should be taken to ensure that the boost voltage is not so high that the motor saturates.

IR compensation, where at light loads the amount of boost voltage is proportional to the amount of current in the motor, is an improvement. Many scalar controls use special algorithms to dynamically compensate for the voltage drop caused by motor stator resistance and inductance. This provides even better starting and operating performance in the low speed region, and, by using additional motor 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 (for example, with centrifugal pumps and fans) and it is particularly useful if multiple motors are to be supplied from a single converter.

4.4.1.2 Vector control

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

This decoupling is achieved by calculation of the motor 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.

4.4.1.3 Direct flux and motor torque control

A direct flux and motor torque controlled converter has a hysteresis (also known as 'sliding mode') control type, which adjusts the flux and the torque of the motor by mathematical model calculation of the motor, 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.

The philosophy is to reach the required motor torque and speed as quickly as possible.

4.4.2 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 motors of different ratings in parallel with one converter (multi-motor operation).
- Scalar control is typically insufficient for dedicated low speed load requirements (below approximately 10 % of base 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 motor torque control is the dynamic response.
- Vector or direct flux and motor 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 motor torque control, multi-motor operation can be realized with or without speed feedback, provided that motors of the same rating are used.
- The characteristics of vector control and those of direct flux and motor torque control are almost equivalent, because both use mathematical model calculations of the motor with or without flux or speed sensors.

Further details are available in IEC 61800-2.

4.5 Converter output voltage generation

4.5.1 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 to be 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.

4.5.2 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.

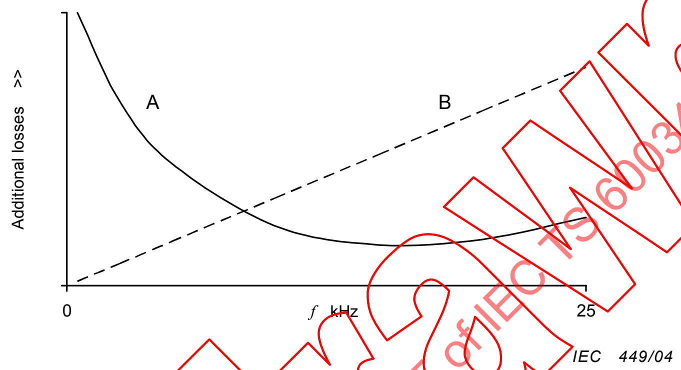
Hysteresis switching can be used with several control parameters: voltage, current, flux or torque, depending on the type of control.

4.5.3 Influence of switching frequency

The converter output switching frequency will affect the losses (in the motor and in the converter), acoustic noise and torque ripple of the overall system. It is not possible to provide precise data on these effects, but they are shown in a general manner by Figure 5, Figure 6 and Figure 7. These figures are for illustration only, and it is not intended that comparative calculations should be made from them.

NOTE 1 In Figure 5, the vertical scales for the motor losses and converter losses are not the same. The converter losses will generally be less than the motor losses.

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 – Motor losses

B – Converter losses

Figure 5 – Effects of switching frequency on motor and converter losses

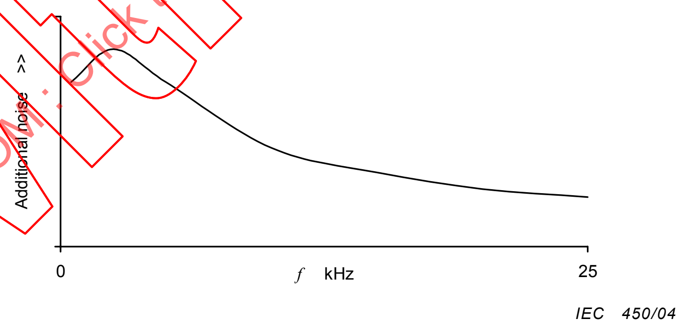
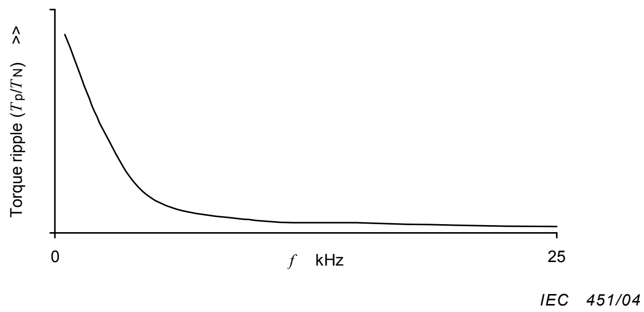


Figure 6 – Effects of switching frequency on acoustic noise



Key

T_p is the peak value of the pulsating torque

T_N is the rated torque

Figure 7 – Effects of switching frequency on torque ripple

4.5.4 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 DC bus voltage.

Multi-level converters 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 converters require more switching semiconductors, they are more common for high-voltage applications (see IEC 61800-4).

4.6 Motor requirements

Table 2 indicates some main individual aspects and design considerations.

Table 2 – Motor design considerations

Required aspect of application	Design consideration
Long term operation at low speed	Thermal oversizing or forced cooling. For long-term operation of sleeve bearings below 10 % of base speed, the bearing performance should be confirmed by the manufacturer.
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). V/Hz characteristic reaches maximum in field weakening region.
Improved motor efficiency with converter supply	Rotor cage designs (no deep bars, see 5.3). May exclude line start and line bypassing capability.
Line bypassing or line start capability	Rotor cage design must 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 % – 40 % (depending on motor size) at near-zero frequencies.
Voltage drop in the converter because of modulation or filter or cabling	Adaptation of the rated motor voltage to compensate for the voltage drop.
Multi-motor operation at approximately synchronized common speed	Similar slip/torque characteristics of the motors.

In some applications, the motor parameters given in Table 3 may be requested from the motor designer for tuning the converter.

Table 3 – Motor parameters

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 motor resonances		Yes, if discrete carrier frequencies occur	
Mechanical parameters			
Inertia	For high rates of acceleration	Optional	Optional
Friction and cooling fan torque demand, specific polynominal in speed ($m = k_1 \times n + k_2 \times n^2$)	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			
Stator resistance (R_s)	At operating temperature	Optional for IR compensation	Yes
Rotor resistance (R_r') (see NOTE)	At operating temperature	Optional for advanced scalar control	Yes
Stator leakage reactance ($X_{\sigma s}$)	At fundamental frequency	Optional for advanced scalar control	Yes
Rotor leakage reactance ($X_{\sigma r}$') (see NOTE)	At rated operating point, different from locked-rotor condition	Optional for advanced scalar control	Yes
Magnetizing reactance (X_m)	At fundamental frequency and rated operating point	Optional for advanced scalar control	Yes
Magnetizing conductance (G_m)	At fundamental frequency and rated operating point	Optional for advanced scalar control	Yes
Magnetizing inductance, specific polynominal	For field weakening	Yes, for advanced scalar control	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, (e.g. ladder equivalent circuit)		Optional	Optional
NOTE The rotor electrical parameters R_r' and $X_{\sigma r}$' are as referred to the stator circuit by the square of the stator/rotor turns ratio.			

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 motor designer to supply data on the internal thermal capacitances and resistances of the component parts of the motor. These parameters may be dependent on both rotational and switching frequency.

5 Losses and their effects

5.1 General

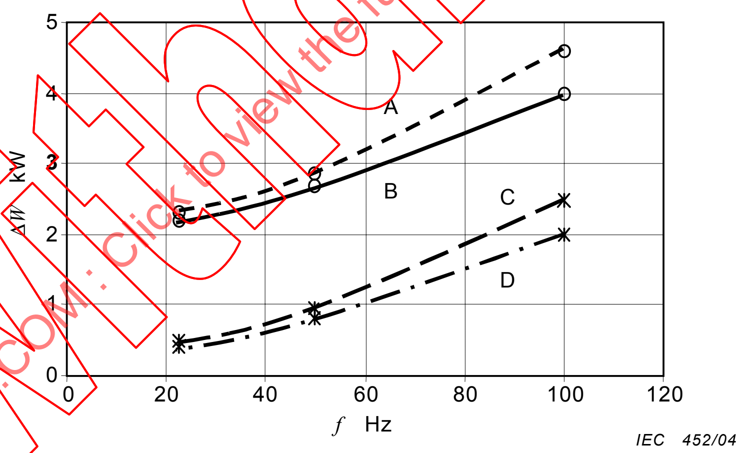
In addition to the well-known losses due to fundamental voltage and currents, the non-sinusoidal supply by a converter creates additional losses in the motor. These additional losses depend on speed, voltage and current, the converter output voltage waveform, and the design and size of the motor. If neither series inductances nor filters are provided, these losses can amount up to 10 % to 20 % of the fundamental losses and thus up to about 1 % to 2 % of the rated output of the motor.

The magnitude and the characteristic behaviour of the additional losses depend on the type and on the parameters of the converters involved as well as on the design of the motor and of the filter circuits.

5.2 Losses in motors supplied from voltage-source converters

Voltage-source converters impress their voltage on the motors connected. Due to the output switching, the average voltage of nearly ideal shape is accompanied by a quasi-rectangular voltage with steep slopes and approximately constant amplitude (two-level converters impress a peak-to-peak value of the intermediate DC voltage). Since this "pulse voltage" is about constant in amplitude and frequency content, these losses are nearly independent of current, speed and flux (voltage) of the motor. So they occur like no-load losses. The influence of saturation (due to flux or to current) on the additional losses is small.

Figure 8 shows examples of the losses at no-load and at full-load for a 37 kW, 50 Hz motor powered from 50 Hz sinusoidal and 5,5 kHz voltage-source converter supplies.



Key

A: full load, PWM supply B: full-load, sine supply C: no load, PWM supply D: no-load, sine supply

Figure 8 – Example of measured losses *W*, as a function of frequency *f* and supply type

Typically, the additional losses show a strong decline with increasing pulse frequency up to a few kHz (see Figure 9).

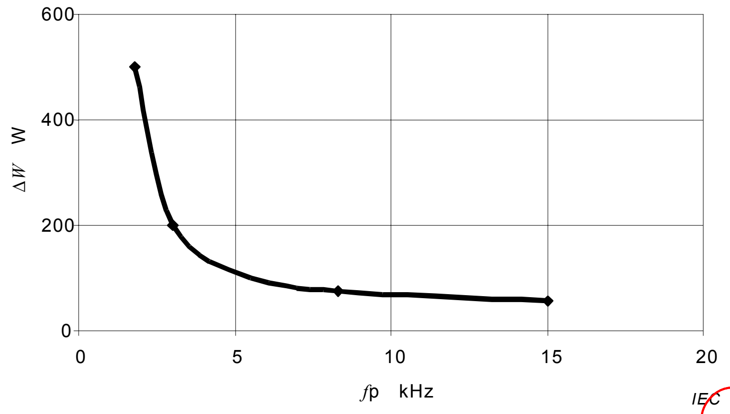


Figure 9 – Additional losses *ΔW* of a motor (same motor as Figure 8) due to converter supply, as a function of pulse frequency *f*p, at 50 Hz rotational frequency

However, the commutation losses in the converter increase with the pulse frequency with the result that the sum of the losses has a minimum at a few kHz.

Typical values for the additional losses due to converter supply are, decreasing with increasing motor size:

0,4 % to 2 % of rated output for two-level converters, and

0,2 % to 1 % of rated output for three-level converters,

with only small variation with flux (voltage) and torque (current) but depending on switching frequency and on fundamental frequency. For hysteresis or random PWM controlled converters, an average switching frequency applies which may also depend on voltage and current.

5.3 Location of the extra losses and ways to reduce them

The converter output voltage approximates a sinusoidal wave using quasi-rectangular voltage pulses. For the pulses, the motor appears as a frequency dependent impedance. The losses of this impedance are mostly due to skin effect in the conductors (mainly rotor bars, in some cases also stator conductors) and to eddy currents in the leakage flux paths (especially in the laminations). The additional losses at the voltage-source converter supply can be minimized by various design measures, for example:

- rotor 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;
- reduced eddy current losses in series inductors or filters.

5.4 Converter features to reduce the motor losses

The most significant benefits are achieved by optimising the motor 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. The fundamental losses may also be reduced by variation of intermediate DC voltage.

NOTE 1 This solution is beneficial to applications where the required torque is a function of the speed, for example pumping and ventilation (torque proportional to the square of the speed). Other applications require careful consideration.

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

- optimising the pulse patterns.
- increasing the switching frequency (see Figure 9).

  NOTE 2 Increasing the switching frequency will result in higher switching losses in the converter (see Figure 5).

- multi-level converter configuration.

5.5 Temperature and 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 motor 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 motor,
- use of a higher thermal insulation classification (see IEC 60034-1),
- full compensation for the intended operating ambient temperature (see IEC 60034-1),
- use of oversized motor,
- optimisation of converter output waveform.

NOTE Increased temperatures may affect not only the winding insulation 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. Duty types S1 to S9 consider the maximum 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, and Annex A of that standard gives a formula for the calculation of thermal life expectancy.

5.6 Determination of motor efficiency

The recommended methods to determine the motor efficiency are given in A.1.6 of IEC 60034-2. For motors of power higher than 50 kW, the summation-of-losses method is preferred.

NOTE A future edition of IEC 60034-2 will probably change this from 50 kW to 150 kW.

The no-load losses (including the additional losses) should be measured at the same pulse pattern and pulse frequency that the converter will produce at rated load.

6 Noise, vibration and oscillating torques

6.1 Noise and vibration in an induction motor supplied from a converter

6.1.1 General

The converter and its function creates 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 base speed. The factors that are influenced are bearings and lubrication, ventilation and any other features that are affected by temperature changes.

- Motor 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 oscillations due to the interaction of waves of different frequencies of the magnetic field in the motor 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 emitted noise level with plain bearings.

6.1.2.2 Rolling element bearings

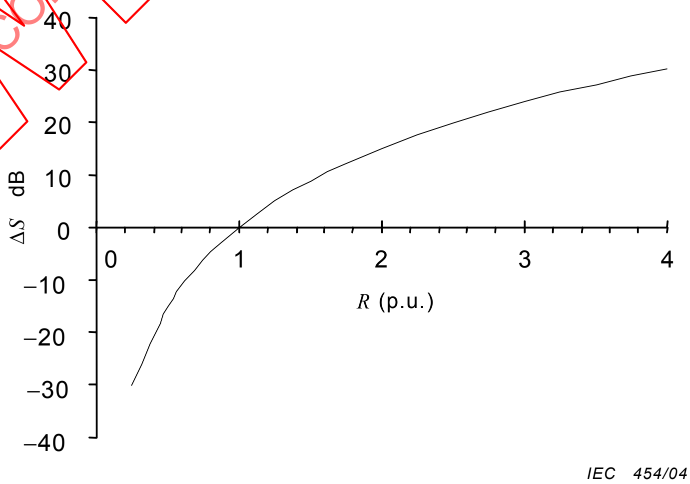
The fundamental frequencies of potential noise emission from a rolling element bearing will vary directly with the rotational speed. If the bearing is "quiet" at the base speed, it is unlikely for the noise level to change significantly when the speed is reduced. However, when the speed is increased above the base speed there is the possibility that the noise level could increase dramatically due to harmonics of the fundamental frequencies being exacerbated due to skidding of the rolling elements. The susceptibility to this phenomena 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 motor'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 10 (for a fan peripheral velocity up to 50 m/s). The fan noise will decrease by about 15 dB for a 50 % reduction in speed and increase by about 10 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 motor with curved unidirectional blades.



Key

ΔS – change in sound pressure R – relative fan speed

Figure 10 – Fan noise as a function of fan speed

6.1.3 Magnetically excited noise

When the motor is to be operated over a wide speed range, resonances are unavoidable due to the varying supply frequencies. This effect is not associated with the converter supply and would also occur in case of variable-frequency sinusoidal supply voltages.

In the case of motors supplied from a converter, the interactions with the motor structure of the spatially varying fundamental fields caused by the time harmonics of the stator and rotor currents should also be considered. 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 motor designer alone and that in many cases design co-operation is essential.

The fairly crude synthesis of a sinusoidal voltage waveform at variable frequency by a voltage source converter produces a very large number of voltage harmonic components and, as a consequence, current harmonic components in stator and rotor. The amplitude and frequencies generated result from the converter pulse control operation and the motor parameters. Experience has shown that with pulse frequencies less than 3 kHz, the harmonic frequencies can be close to the natural frequencies of the motor core and structure on medium and large motors and consequently with wide speed range applications, resonance points are nearly unavoidable at some point in the speed range. The resonance frequencies for the modes $r = 0$ and $r = 2p$ are less than 2,5 kHz for 2-pole and 4-pole motors 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 motors.

The increment of noise of motors supplied from PWM controlled converters compared with the same motor 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.

In some circumstances, it may be necessary to create ”skip bands” in the operating speed range in order to avoid specific resonance conditions due to the fundamental frequency.

6.1.4 Torsional oscillation

Oscillating torques are generated in the shaft of motors 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 the case of voltage source PWM converters with low pulse frequencies (less than 200 Hz), the oscillating torques can be up to 50 % rated torque depending on the harmonic content of the output voltage. In the case of converters with much higher pulse frequencies of greater than 2 kHz, the significant oscillating torques at 6 and 12 times fundamental frequency are always less than 10 % of rated torque.

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. Bear 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.

6.2 Sound power level determination and limits

6.2.1 Methods of measurement

Sound power levels should be determined in accordance with IEC 60034-9 (but see 6.2.2).

6.2.2 Test conditions

Tests should be made with the motor supplied from a converter with the pulse frequency and pattern that will be used in the application.

It is preferred that the motor should be rigidly mounted to a surface representative of the installed operating condition.

During the test, it is preferred that a preliminary measurement should be made over the entire speed and load range to determine the conditions for maximum noise, and a final measurement should then be made under these conditions.

If the above conditions cannot be achieved, the test conditions of IEC 60034-9 should be used.

6.2.3 Sound power level limits

Where a motor is tested under the conditions specified in 6.2.2, it is recommended that the sound power levels should not exceed the values specified in Table 4.

NOTE The values in Table 4 are different from those in IEC 60034-9. However, they represent sound power levels that are achievable with current technology.

If the limits in Table 4 cannot be achieved due to resonant effects, consideration should be given to the inclusion of appropriate "skip bands" in the operating mode.

Table 4 – Sound power level as a function of output power

	On-load sound power level (dBA)	
Power output at maximum speed (kW)	**Less than 2 000 r/min**	**2 000 r/min to 3 750 r/min**
≤ 2,2	80	86
5,5	84	90
11	88	94
22	92	98
37	95	101
55	98	104
110	100	106
220	104	110
550	110	116

6.3 Vibration level determination and limits

6.3.1 Method of measurement

Vibration levels should be determined in accordance with IEC 60034-14.

6.3.2 Test conditions

Tests should be made with the motor supplied from a converter with the pulse frequency and pattern that will be used in the application.

It is preferred that the motor should be rigidly mounted to a surface representative of the installed operating condition.

During the test, it is preferred that a preliminary measurement should be made over the entire speed and load (see NOTE 1) range to determine the conditions for maximum vibration and that a final measurement should then be made under this condition.

NOTE 1 This recommendation can significantly increase the test time, and is not required by IEC 60034-14.

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

6.3.3 Vibration level limits

When testing under the conditions specified in 6.3.2 it is recommended that the vibration magnitude measured on the bearing housings should not exceed the vibration level Grade A, given in Table 1 of IEC 60034-14.

7 Motor insulation electrical stresses

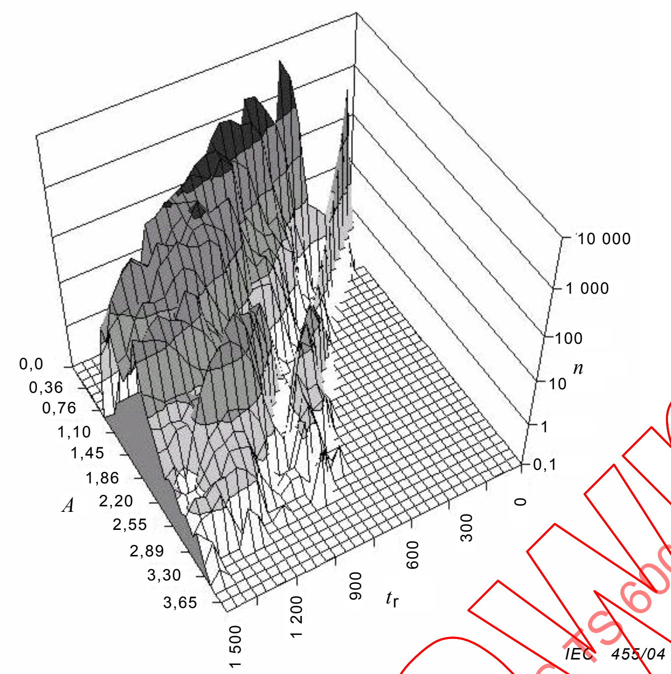
7.1 General

The insulation system of the motor 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 not more than the DC bus voltage (1 p.u.). This level depends on the rectified mains voltage or braking voltage level or power factor correction regulation voltage.

Modern converter output voltage rise times may be in the 50 ns to 400 ns range. They are kept as short as possible to minimize switching losses in the output semiconductors. These converters can generate repetitive voltage overshoots at the terminals of a motor connected by a cable, which can reduce the life of a motor insulation system if they exceed its repetitive voltage strength. Figure 11 shows a plot of the surge count measured at the terminals of a motor fed from a converter. As can be seen, there is not a simple relationship between the surge count and the surge rise time and magnitude.

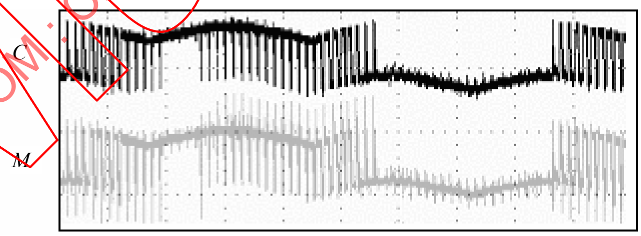


Key

A – surge magnitude (p.u.) t_r – surge rise time (ns) *n* – surge count (per second)

Figure 11 – Typical surges at the terminals of a motor fed from a PWM converter

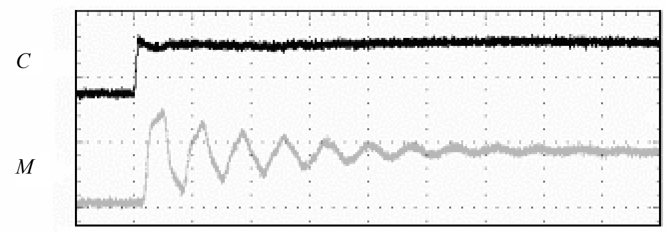
Depending on the rise time of the voltage pulse at the converter output, and on the cable length and motor impedance, the pulses generate voltage overshoots at the motor terminals (typically up to 2 p.u. between phases). These voltage overshoots are created by reflected waves at the interface between cable and motor terminals due to impedance mismatch. 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 frequencies present in the voltage waveform will increase. Typical voltage surges measured at a converter output and at the motor terminals are given in Figure 12 with an enlarged view of one surge shown in Figure 13.



Key

C – phase voltage at converter *M* – phase voltage at motor

Figure 12 – Typical voltage surges on one phase at the converter and at the motor terminals (2 ms/division)



IEC 457/04

Key

C – phase voltage at converter *M* – phase voltage at motor

Figure 13 – Individual short rise time surge from Figure 12 (1 µs/division)

As the cable length increases, the pulse overshoot generally increases to a maximum then declines. Meanwhile, the pulse rise time at the motor terminals increases. For short rise time pulses (at the converter output) with cable lengths exceeding about 20 m to 50 m (depending on cable type and other factors), the voltage rise time at the motor terminals is determined mainly by the cable characteristics and no longer by the rise time at the converter.

Voltage overshoots are decreased in the case of installations using a decentralized topology (converters installed close to associated motors), where the cable length between converter and motor is short.

Voltage overshoots do not occur if the converter is integrated into the motor, so that the cable length between converter and motor is limited to only some 10 cm.

Higher voltage stress over 2 p.u. can be produced by converter double transition (cross-switching) and by the lack of an algorithm in the converter to set a minimum time between pulses:

- double transition occurs for example when one phase switches from minus to plus DC bus voltage at the same instant that another phase switches from plus to minus. This generates a 2 p.u. voltage wave which travels to the motor. This can then build to greater than 2 p.u. over-voltage when reflected at motor terminals.
- if there is no minimum pulse time control in the converter, and if the time between two pulses is matched with the time constant of the cable between the converter and the motor, an over-voltage greater than 2 p.u. can be generated at the motor terminals.

7.3 Winding electrical stress

The dielectric stress of the winding insulation is determined by the peak voltage and the rise time (for definition, see Figure 14) of the impulse at the motor terminals, and on the frequency of the impulses produced by the converter.

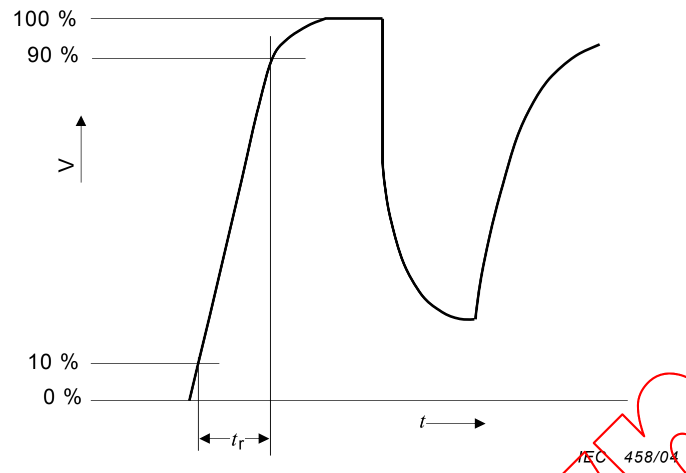
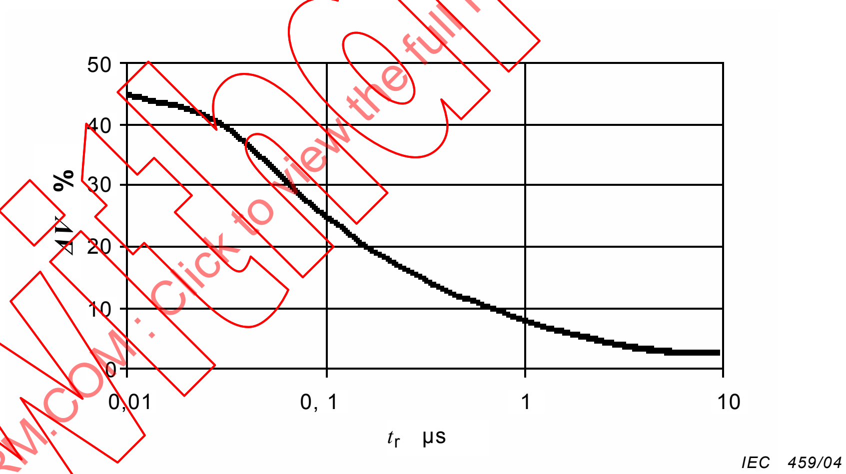


Figure 14 – Definition of the peak rise time t_r of the voltage at the motor terminals

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 within the first few turns at the line end of the individual phase winding. Figure 15 shows an example of the distribution of the voltage across a 50-turn coil as a function of the impulse rise time. As illustrated, the shorter the rise time, the more voltage appears across the first turn of the coil.



Key

ΔV – voltage across the first turn (% of input voltage) t_r – surge rise time

Figure 15 – First turn voltage as a function of the surge rise time

Short rise time impulses at motor terminals also cause high wire to wire voltages in the first turns of each winding phase and can be followed by early dielectric breakdown wire to wire. Such occurrences are often due to inadequate dielectric strength of the enamel coating. In this case, the dielectric breakdown occurs well under the Partial Discharge Inception Voltage (PDIV) level. Insulation failures of this type cannot be detected by a standard dielectric test at 50 Hz or 60 Hz. New methods of verification are being developed to test for such insulation breakdowns. It can be observed that the voltage rise time at the motor terminals increases with the length of the cable due to high frequency losses in the cable.

7.4 Insulation stress limitation

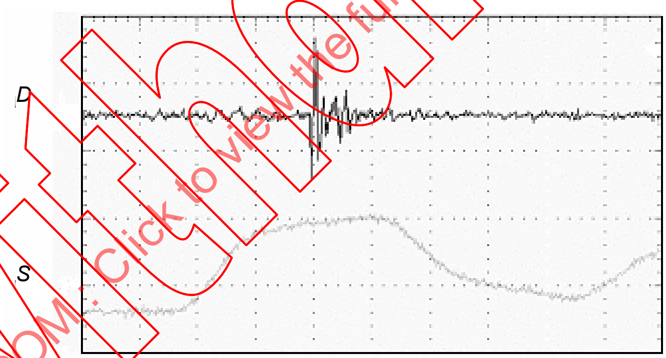
The upper limited level at which this over-voltage stress becomes harmful is the PDIV (the voltage at which partial discharges begin to occur) or, in the air, the Corona Inception Voltage (CIV). Partial discharges cause degradation of the insulation system through both chemical and mechanical erosion.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

PDIV and CIV in a motor are influenced by:

- Winding type: random or form wound.
- Design: phase separation material.
- Varnish type and impregnation.
- 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).

Figure 16 shows a partial discharge pulse that has resulted from a surge on one phase of a converter-fed motor.

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.



IEC 460/04

Key

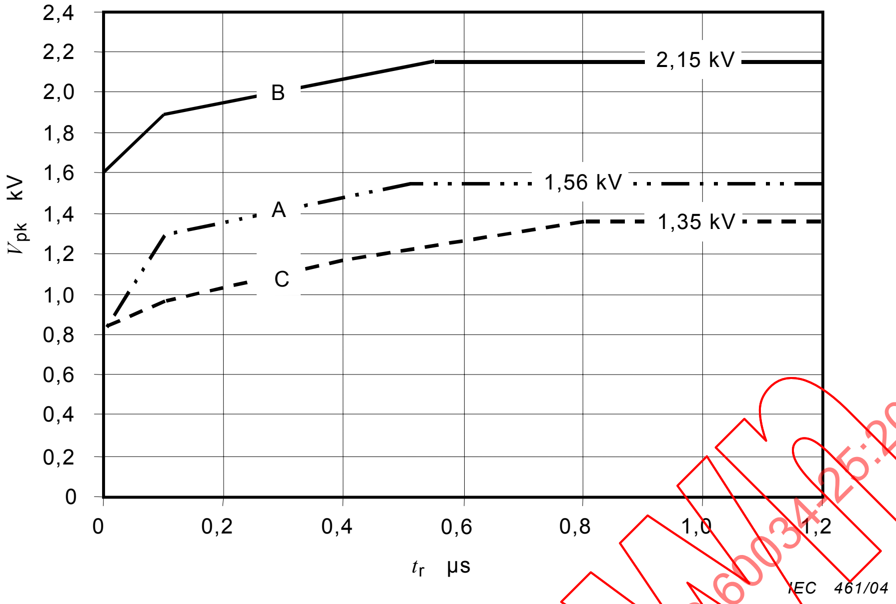
S – voltage surge at motor terminals *D* – discharge pulse

Figure 16 – Discharge pulse occurring as a result of converter generated voltage surge at motor terminals (100 ns/division)

7.5 Responsibilities

The system supplier should ensure that the voltage stress level does not exceed the insulation system voltage stress capability (see Figure 17). Therefore, the system supplier is responsible for specifying the voltage stress level at the motor terminals, taking into account possible voltage reflection depending on the topology and operating mode of the converter, cable type and length, etc. Relevant parameters for insulation stress are: transient peak voltage values, rise time, repetition rate, etc.

The motor manufacturer should check the voltage stress withstand capability according to the system supplier's specification. To ensure that no service lifetime reduction of the motor insulation occurs, the actual stress due to converter operation should be lower than the repetitive voltage stress withstand capability of the motor winding insulation system (level A or B of Figure 17).



Key

B – without filters for motors up to 690 V AC

A – without filters for motors up to 500 V AC

C – curve from IEC 60034-17

Figure 17 – Limiting curves of impulse voltage V_{pk}, measured between two motor phase terminals, as a function of the impulse rise time t_r

7.6 Converter characteristics

The amplitude of the output voltage pulses is in general the DC bus voltage, which depends on the mains supply voltage and the type of input rectifier (passive or active, with or without voltage boost) and usually increases at regenerative operation (for example, when braking).

The rise time of the pulses depends on the switching characteristics of the power semi-conductors and their driver and eventually their snubber circuits.

NOTE The rise time at the terminals of the motor is not directly related to the rise time at the output of the converter and these two should not be confused. The relationship between them is complex and depends on the high frequency characteristics of the motor and of the cable. The rise time referred to in Figure 17 is the value at the motor terminals, not the value at the converter terminals. When designing a PDS, using the expected rise time at the converter terminals (which will be defined) instead of the rise time at the motor terminals (which is difficult to predict) introduces a safety margin to be compared with cost consequences.

7.7 Methods of reduction of voltage stress

There are several possible methods of reducing the surge severity in a given situation:

- Although it is often difficult or impractical, changing the cable length and/or grounding of the cable between the motor and converter will change the surge magnitudes seen by the motor.
- Changing the installation to one using a decentralized topology, or using integrated motor/converter combinations, will decrease the voltage overshoots.
- Replacing the cable with a type with higher dielectric losses (e.g. butyl rubber or oil-paper). Special types of motor cables using ferrite shielding are available. These reduce the voltage oscillations and improve the EMC quality.
- Installing an output reactor (see 9.2.2) will increase the rise time of the travelling wave in combination with the cable capacitance.

  NOTE In this case, the voltage drop across the inductance should be taken into account in the system design.

- Installing an output dV/dt filter (see 9.2.3) between the converter and the cable leading to the motor will significantly lengthen the rise time of the surges. This option may allow the use of longer cables.
- Installing an output sinusoidal filter (see 9.2.4) will increase the rise time. However, the main function of such a filter is to reduce EMC interference and additional motor losses and noise. Also, with a nearly sinusoidal voltage, standard unscreened cables can be used. The possibility of using this solution depends on the required characteristics, particularly the speed range and dynamic performance, of the application.
- Installing a motor termination unit (see 9.2.5) at the motor terminals will suppress the overvoltages at the motor terminals.
- Preventing cross-switching of converter phases.
- Controlling the converter minimum inter-pulse time (depending on cable type and length).
- Replacing the converter with one producing smaller voltage steps, for example, a three-level converter.

7.8 Motor choice

The admissible impulse voltage stress for an insulation system is determined by its design. In general, three impulse withstand levels as shown in Figure 17 are available for low-voltage induction motors:

- Withstand level according to IEC 60034-17:

  When using converters without any reduction methods as described in 7.7, such motors are suitable for drive systems only up to 400 V AC supply voltage within a restricted range of cable length. In addition, the control of the converter has to prevent double transitions and provide a minimum pulse time control.

  When using filtering devices as described in 7.7 (integrated in the converter or installed in the system), such motors can be used for drive systems up to 690 V AC supply voltage and without limits of cable length.
- Withstand level according to curve A in Figure 17:

  When using converters without any reduction methods as described in 7.7, such motors are suitable for drive systems up to 500 V AC supply voltage. Again, the control of the converter has to prevent double transitions and provide a minimum pulse time control.
- Withstand level according to curve B in Figure 17:

  When using converters without any reduction methods as described in 7.7, such motors are suitable for drive systems up to 690 V AC supply voltage. Again, the control of the converter has to prevent double transitions and provide a minimum pulse time control.

8 Bearing currents

8.1 Sources of bearing currents in converter-fed motors

8.1.1 General

Several situations can cause bearing currents. In all cases, bearing current will flow when a voltage is developed across the bearing sufficient to break down the insulating capacity of the lubricant. There are several sources of this voltage.

8.1.2 Magnetic asymmetry

Asymmetry in the magnetic circuit of a motor creates a situation that causes low frequency bearing currents. This is more common in motors greater than 400 kW. An asymmetric magnetic circuit results in a circumferential AC flux (ring flux) in the yoke. This induces an AC voltage of the conductive loop comprising the motor shaft, the bearings, the end brackets, and the outer frame of the 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.

8.1.3 Electrostatic buildup

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 voltages

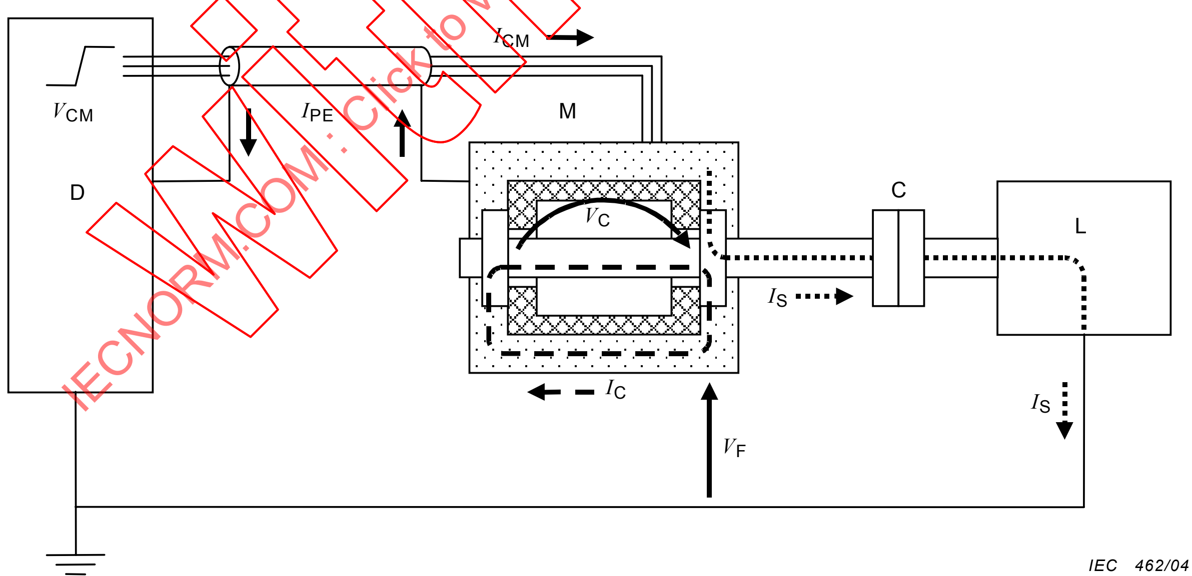
The high-frequency common mode voltage at the motor terminals generates common mode currents, part of which may flow through the bearings of the motor or of the driven equipment. The common mode currents may also generate a voltage across the bearings by transformer action. These effects result from the use of fast switching semiconductor devices, and can cause bearing problems, due to different effects, in motors of all ratings. These effects are described in detail in 8.2.

8.2 Generation of high frequency bearing currents

8.2.1 General

The most important factors that define which mechanism is prominent are the size of the motor and how the motor frame and shaft are grounded. The electrical installation, meaning a suitable cable type and proper bonding of the grounding conductors and the electrical shield, also plays an important role, as well as the rated converter input voltage and the rate of rise of the converter output voltage. The source of bearing currents is the voltage across the bearing. There are three types of high frequency bearing currents: circulating, shaft grounding, and capacitive discharge.

Two types of bearing currents, high frequency circulating current (I_C) and shaft grounding current (I_S), are shown schematically in Figure 18. These are strongly influenced by the grounding arrangements and grounding impedances.



Key

D – converter M – motor C – shaft coupling L – driven load

V_{CM} – high frequency (HF) common-mode voltage

→ I_{CM} : HF common-mode current → V_S : HF shaft voltage → I_C : HF circulating current

→ I_{PE} : HF return current → V_F : HF frame voltage → I_S : HF shaft current

Figure 18 – Possible bearing currents

8.2.2 Circulating current

In large motors, a high frequency voltage is induced in the closed loop described in 8.1.2 by the high frequency flux circulating around the stator yoke. This flux is caused by capacitive currents leaking from the winding into the stator laminations. The induced shaft voltage may affect the bearings. If it is high enough to overcome the insulation of the bearings' lubricant film, a compensating current to balance the flux in the stator flows, looping the shaft, the bearing and the stator frame.

These high-frequency currents may be superimposed on low-frequency currents generated as described in 8.1.2.

8.2.3 Shaft grounding current

The current leaking into the stator frame needs to flow back to the converter, which is the source of the current. Any route back contains impedance, and therefore, the voltage of the motor frame increases in comparison to the source ground level. If the motor shaft is earth grounded via the driven machinery, the increase of the motor frame voltage is seen across the bearings. If the voltage rises high enough to overcome the insulating capability of the bearing lubricant film, part of the current may flow via that bearing, the shaft and driven machine back to the converter.

8.2.4 Capacitive discharge current

The internal voltage division of the common mode voltage over the internal capacitances of the motor may cause bearing voltages high enough to create high frequency bearing current pulses (referred to as Electrostatic Discharge Machining currents). This can happen if the shaft is not grounded via the driven machinery while the motor frame is tied to ground for protection.

8.3 Common-mode circuit

8.3.1 General

A common mode circuit is a closed loop path for circulating current flow within the entire system, including the motor and its bearings, the load and the converter.

A typical three phase sinusoidal power supply is balanced and symmetrical under normal conditions. Thus the neutral voltage is zero. However, this is not the case with a PWM switched three phase power supply, where the DC voltage is converted into three phase voltages. Even though the fundamental frequency components of the output voltages are symmetrical and balanced, it is impossible to make the sum of the three output voltages instantaneously equal to zero with only two possible output levels available. The resulting neutral point voltage is not zero. This voltage is the common mode voltage source. It is measurable at the star point of the motor winding (or at an artificial star point for motor windings other than star) at any load. The voltage is proportional to the DC bus voltage, and its significant frequency is equal to the converter switching frequency.

Any time one of the three converter outputs is changed from one of the possible potentials to another, a current proportional to this voltage change is forced to flow to earth via the earth capacitances of all the components of the output circuit. The current flows back to the source via the earth conductor and capacitances of the converter.

8.3.2 System common-mode current flow

The return path of the leakage current from the motor frame back to the converter frame consists of the motor frame, cable shielding or ground conductors and possibly conductive parts of the factory building structure. All these elements contain inductance. The flow of common mode current through such inductance will cause a voltage drop that raises the motor frame potential with respect to the converter frame. This motor frame voltage 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 motor frame, the 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 inductance is high enough, voltage drops of over 100 V may occur between the motor frame and the converter frame. If, in such a case, the 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 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 machine bearings. These bearings may be damaged before the motor bearings.

8.4 Stray capacitances

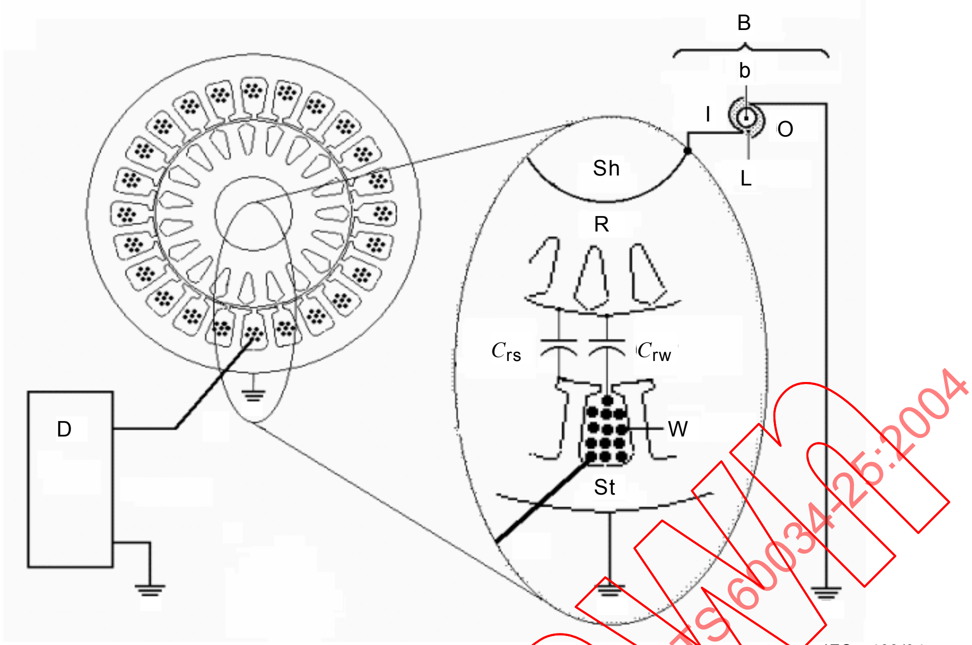
8.4.1 General

The stray capacitances inside the motor (see Figure 19) are very small, and present a high impedance for low frequencies thus blocking the low frequency currents. However, fast rising pulses produced by modern converters contain frequencies so high that even the small capacitances inside the motor provide a low impedance path for current to flow.

8.4.2 Major component of capacitance

The largest share of the motor's capacitance is formed between the stator windings and the motor frame. This capacitance is distributed around the circumference and length of the stator. As the current leaks into the stator along the coil, the high frequency content of the current entering the stator coil is greater than the current leaving it.

This net axial current produces a high frequency magnetic ring flux circulating in the stator laminations, inducing an axial voltage in the loop described in 8.1.2. If the shaft voltage becomes large enough, a high frequency circulating current can flow through the shaft and both bearings and, in some cases, through the shaft and bearings of the load machine. 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 motor, the rate of rise of the voltage at the motor terminals and the DC link voltage level.



Key

D – Converter	Sh – Shaft	R – Rotor	St – Stator
W – Winding	Crs – Rotor-stator capacitance	Crw – Rotor-winding capacitance	B – Bearing
b – ball or roller	I – Inner race	O – Outer race	L – Lubricant film

Figure 19 – Motor capacitances

8.4.3 Other capacitances

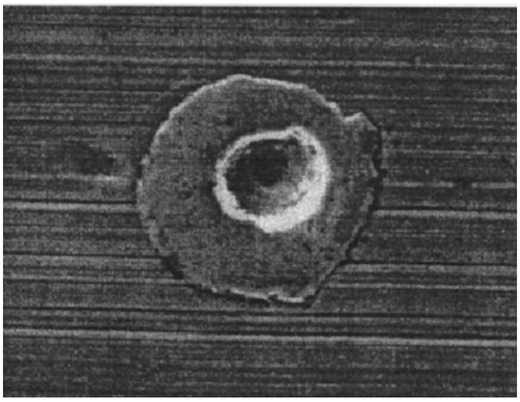
The capacitance between the stator winding and the laminations is an important element of the common mode circuit. There are other capacitances, such as the capacitance between the overhang of the stator windings and the rotor, or that existing in the motor's air gap between the stator iron and the rotor surface. The bearings themselves also have capacitance.

Fast changes in the common mode voltage from the converter cannot only result in currents in the capacitance around the circumference and length of the motor, but also between the stator windings and the rotor into the bearings.

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 balls of the 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.

8.5 Consequences of excessive bearing currents

Figure 20 and Figure 21 show typical bearing damage due to common mode currents and electrical discharge.



IEC 464/04

Figure 20 – Bearing pitting due to electrical discharge (pit diameter 30 µm to 50 µm)

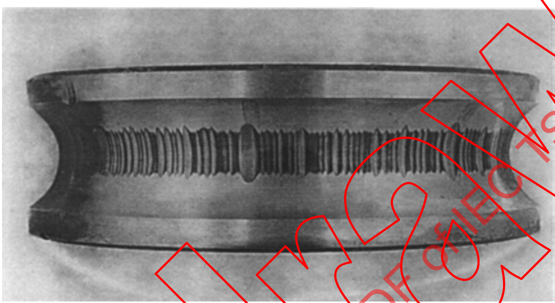


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Figure 21 – Fluting due to excessive bearing current

8.6 Preventing high frequency bearing current damage

8.6.1 Basic approaches

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

- a proper cabling and grounding system;
- modifying the bearing current loops;
- 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 grounding system. Standard equipment grounding 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 at the high common mode current frequencies, if the installation follows the principles of Clause 9.

8.6.2 Other preventive measures

- Use insulated bearing(s).

  NOTE 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.

- Use a filter that reduces common-mode voltages and/or dv/dt.

- Use non-conductive couplings for loads or other devices which may be damaged by bearing currents.
- Use brush contact(s) between shaft and motor frame.
- Use lower voltage motor and converter if possible.
- Run the converter at the lowest switching frequency that satisfies audible noise and temperature requirements.
- Avoid the use of double transitions (parallel switching).

Table 5 compares the effectiveness of some of these measures.

Table 5 – Effectiveness of bearing current countermeasures

Counter measure	Current type			Additional comments
	Circulating currents (8.1.2, 8.2.2)	Shaft grounding currents (8.2.3)	Capacitive discharge currents (8.2.4)	
1) NDE insulated, or ceramic rolling elements	Effective	Not effective: Only protects one bearing.	Not effective: Only protects one bearing.	NDE insulated to avoid need for an insulated coupling.
2) NDE and DE insulated, or ceramic rolling elements	Effective: One insulated bearing is adequate for this current type.	Effective	Effective: May require additional brush contact.	Most effective for small frame sizes. Less practical for large frame sizes.
3) NDE and DE insulated, or ceramic rolling elements + additional insulated coupling and shaft grounding brush	Effective	Effective	Effective	Most effective (especially for larger machines). Helps to prevent possible damage to driven load. Servicing necessary.
4) NDE insulated **One DE brush contact**	Effective: Brush unnecessary for this current type. NDE tachometer bearing, if fitted, needs protection.	Effective: Does not protect bearings in driven load.	Effective: Care needed to ensure low brush contact impedance.	Servicing necessary. Most practical for large frame sizes. DE brush used to avoid need for an insulated coupling.
5) One brush contact **No bearing insulation**	Not effective: Only protects one bearing.	Effective: Does not protect bearings in driven load.	Effective: Care needed to ensure low brush contact impedance.	Servicing necessary.
6) Two brush contacts, DE and NDE **No bearing insulation**	Effective: Care needed to ensure low brush contact impedance.	Effective: Does not protect bearings in driven load.	Effective: Care needed to ensure low brush contact impedance.	Servicing necessary.
7) Low resistance lubrication and/or carbon-filled bearing seals	Poor	Poor	Effective: Depends on condition of materials.	No long term experience. Lubrication effectiveness reduced.
8) Rotor in Faraday cage	Not effective	Not effective	Very effective	Problems from converter generated circulating currents that normally only occur in larger motors.

Counter measure	Current type			Additional comments
	Circulating currents (8.1.2, 8.2.2)	Shaft grounding currents (8.2.3)	Capacitive discharge currents (8.2.4)	
9) 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.
10) Insulated coupling	Not effective	Very effective	Not effective	Also prevents possible damage to driven load.
11) Frame to driven load connection	Not effective	Effective	Not effective	Also prevents possible damage to driven load.
DE = Drive End; NDE = Non Drive End.				

9 Installation

9.1 Grounding, 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 motor cables, and on reliability and EMC installation issues. For specific installations, local regulations concerning grounding 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. See also IEC 61000-5-1 and IEC 61000-5-2 for comprehensive guidance on general EMC installation techniques.

9.1.2 Grounding

9.1.2.1 Objectives of grounding

The objectives of grounding are safety and reliable, interference-free, operation. Traditional grounding 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 grounding 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 grounding strongly attenuates motor shaft and frame voltages, reducing high frequency bearing currents and preventing premature bearing failure and possible damage to auxiliary equipment (see Clause 8).

9.1.2.2 Grounding cables

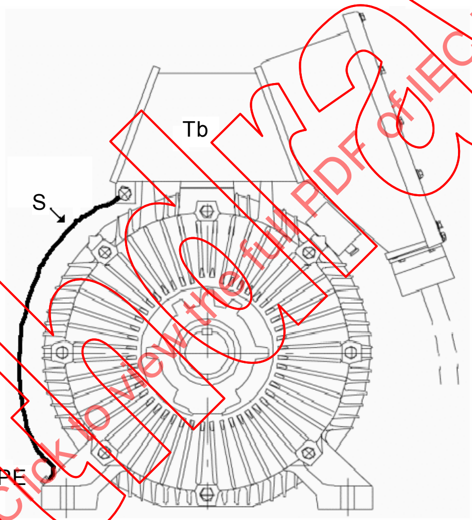
For safety, grounding cables are dimensioned on a case-by-case basis in accordance with local regulations. The appropriate selection of cable characteristics and cabling rules also helps to decrease the levels of electrical stresses applied to the different components of the PDS, and therefore increases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

9.1.3 Bonding of motors

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 braided straps are better. A typical dimensional length/width ratio for these straps should be less than five.

With motors from 100 kW upwards, the external grounding conditions of the driven machinery may require a bonding connection between the motor 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 grounding. It should have low inductance, so a metal strip or braided strap should be used, and it should follow the shortest possible route. In some cases, additional bonding of the motor components, for example between the motor frame and the terminal box, may be required (see Figure 22).

Where a common lubrication system is used for motor and driven load, care must be taken to prevent coupling across insulated bearing housings.



Key

Tb – Terminal box PE – connection to motor frame S – Bonding strap

Figure 22 – Bonding strap from motor terminal box to motor frame

9.1.4 Motor power cables

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.

Shielded multicore cables are preferred for lower powers and easy installation. Up to 30 kW motor 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.

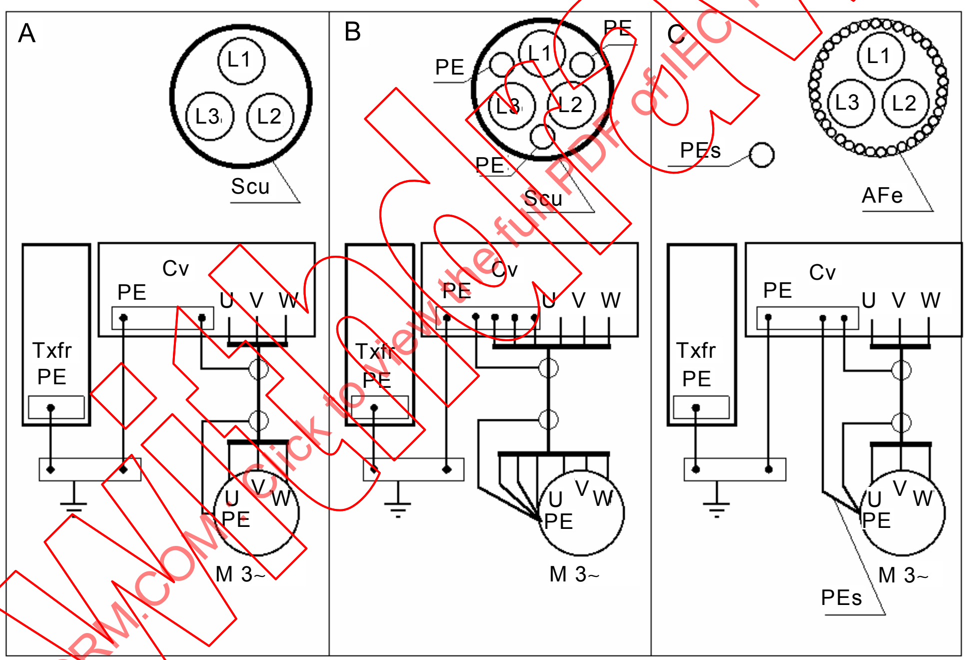
To operate as a protective conductor, the shield conductance should be at least 50 % of the phase conductor conductance. At high frequency, the shield conductance should be at least 10 % of the phase conductor conductance. These requirements are easily met with a copper or aluminium shield/armour. Because of its lower conductivity, a steel shield requires a larger cross-section, and the shield helix should be of low-gradient. Galvanising 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 motor 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 23 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 grounding and a concentric shield/armour (see Figure 23 B). The shield of this cable type is for EMC and physical protection only.

  NOTE For low-power systems, a single conductor for protective grounding may be satisfactory.
- three-core cable with a steel or galvanized iron, low pitch, stranded armour/shield (see Figure 23 C). If the shield has an insufficient cross-section for use as a protective conductor, a separate grounding conductor is needed.



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Scu – concentric copper (or aluminium) screen   AFe – steel armour   Txfr – transformer   Cv – converter   PEs – separate ground wire

Figure 23 – Examples of shielded motor 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 motor 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 motor does not need to be shielded or symmetrical, but the motor may require additional grounding.

Single core unshielded cables may be suitable for motor 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 motor, 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 24.

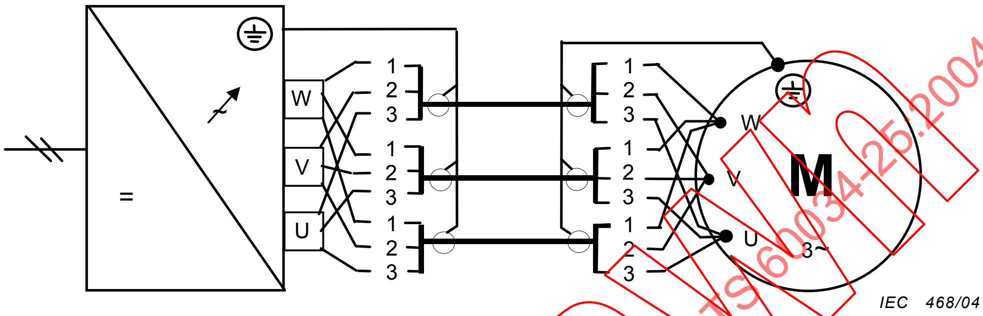

Figure 24 – Parallel symmetrical cabling of high-power converter and motor

9.1.4.3 Cable terminations

When installing the motor cable, it should be ensured that the shield is high frequency (HF) connected to both the converter and the motor enclosure. This requires that the motor 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 motor ends with lower power are shown in Figure 25 and Figure 26 respectively.