TECHNICAL SPECIFICATION

IEC
TS 60034-25

Second edition
2007-03

Rotating electrical machines –

Part 25:
Guidance for the design and performance of a.c. motors specifically designed for converter supply

Reference number
IEC/TS 60034-25:2007(E)

Publication numbering

As from 1 January 1997 all IEC publications are issued with a designation in the 60000 series. For example, IEC 34-1 is now referred to as IEC 60034-1.

Consolidated editions

The IEC is now publishing consolidated versions of its publications. For example, edition numbers 1.0, 1.1 and 1.2 refer, respectively, to the base publication, the base publication incorporating amendment 1 and the base publication incorporating amendments 1 and 2.

Further information on IEC publications

The technical content of IEC publications is kept under constant review by the IEC, thus ensuring that the content reflects current technology. Information relating to this publication, including its validity, is available in the IEC Catalogue of publications (see below) in addition to new editions, amendments and corrigenda. Information on the subjects under consideration and work in progress undertaken by the technical committee which has prepared this publication, as well as the list of publications issued, is also available from the following:

- **IEC Web Site (www.iec.ch)**

- **Catalogue of IEC publications**

  The on-line catalogue on the IEC web site (www.iec.ch/searchpub) enables you to search by a variety of criteria including text searches, technical committees and date of publication. On-line information is also available on recently issued publications, withdrawn and replaced publications, as well as corrigenda.

- **IEC Just Published**

  This summary of recently issued publications (www.iec.ch/online_news/ justpub) is also available by email. Please contact the Customer Service Centre (see below) for further information.

- **Customer Service Centre**

  If you have any questions regarding this publication or need further assistance, please contact the Customer Service Centre:

  Email: custserv@iec.ch
  Tel: +41 22 919 02 11
  Fax: +41 22 919 03 00

TECHNICAL SPECIFICATION

IEC
TS 60034-25

Second edition
2007-03

Rotating electrical machines –

**Part 25:
Guidance for the design and performance of a.c.
motors specifically designed for converter supply**

Commission Electrotechnique Internationale
International Electrotechnical Commission
Международная Электротехническая Комиссия

PRICE CODE **XB**

For price, see current catalogue

CONTENTS

INTERNATIONAL ELECTROTECHNICAL COMMISSION
_____

ROTATING ELECTRICAL MACHINES –

Part 25: Guidance for the design and performance of a.c. motors specifically designed for converter supply

FOREWORD

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

2) The formal decisions or agreements of IEC on technical matters express, as nearly as possible, an international consensus of opinion on the relevant subjects since each technical committee has representation from all interested IEC National Committees.

3) IEC Publications have the form of recommendations for international use and are accepted by IEC National Committees in that sense. While all reasonable efforts are made to ensure that the technical content of IEC Publications is accurate, IEC cannot be held responsible for the way in which they are used or for any misinterpretation by any end user.

4) In order to promote international uniformity, IEC National Committees undertake to apply IEC Publications transparently to the maximum extent possible in their national and regional publications. Any divergence between any IEC Publication and the corresponding national or regional publication shall be clearly indicated in the latter.

5) IEC provides no marking procedure to indicate its approval and cannot be rendered responsible for any equipment declared to be in conformity with an IEC Publication.

6) All users should ensure that they have the latest edition of this publication.

7) No liability shall attach to IEC or its directors, employees, servants or agents including individual experts and members of its technical committees and IEC National Committees for any personal injury, property damage or other damage of any nature whatsoever, whether direct or indirect, or for costs (including legal fees) and expenses arising out of the publication, use of, or reliance upon, this IEC Publication or any other IEC Publications.

8) Attention is drawn to the Normative references cited in this publication. Use of the referenced publications is indispensable for the correct application of this publication.

9) Attention is drawn to the possibility that some of the elements of this IEC Publication may be the subject of patent rights. IEC shall not be held responsible for identifying any or all such patent rights.

The main task of IEC technical committees is to prepare International Standards. In exceptional circumstances, a technical committee may propose the publication of a technical specification when

- the required support cannot be obtained for the publication of an International Standard, despite repeated efforts, or

- 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.

This second edition cancels and replaces the first edition published in 2004.

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

a)   replacement of the original introduction by a shorter introduction;
b)   extension of the scope to include all converter-fed motors, not just LV-induction motors;
c)   minor changes throughout Clauses 4 to 9;
d)   addition of subclauses 4.3.4, 4.3.5, 5.4, 6.2.1, 8.6.3, 8.7 and 8.8, and Figure 7;
e)   inclusion of subclauses 4.4 and 4.5 in Annex A;
f)   expansion of original Annex A which becomes Annex B;
g)   re-drafting of Clause 5;
h)   upgrading of 6.1.4 to 6.3;
i)   removal of noise limits from normative text;
j)   addition of reference to IEC 60034-9;
k)   addition of Annex C.

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

Enquiry draft	Report on voting
2/1406/DTS	2/1420A/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 the maintenance result date indicated on the IEC web site under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

• transformed into an International standard,

• reconfirmed,

• withdrawn,

• replaced by a revised edition, or

• amended.

A bilingual version of this technical specification may be issued at a later date.

INTRODUCTION

The performance characteristics and operating data for *converter*-fed motors are influenced by the complete drive system, comprising supply system, *converter*, cabling, motor, mechanical shafting and control equipment. Each of these components exists in numerous technical variants. Any values quoted in this technical specification 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 technical specification to specify numerical or limiting values for all the quantities which are of importance for the design of the drive system.

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

This technical specification deals with a.c. motors which are specifically designed for *converter* supply. *Converter*-fed motors within the scope of IEC 60034-12, which are designed originally for mains supply, are covered by IEC 60034-17.

Clauses 5 to 9 of this technical specification consider mainly the requirements for low voltage induction motors fed from voltage-source *converters* (U-*converters*). Clauses 10 to 16 provide additional information for other configurations.

ROTATING ELECTRICAL MACHINES –

Part 25: Guidance for the design and performance of a.c. motors specifically designed for converter supply

1 Scope

This part of IEC 60034 describes the design features and performance characteristics of a.c. motors specifically designed for use on *converter* supplies. It also specifies the interface parameters and interactions between the motor and the *converter* including installation guidance as part of a *power drive system*.

The general requirements of relevant parts of the IEC 60034 series of standards also apply to motors within the scope of this technical specification.

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

NOTE 2 This technical specification 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 specification.

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, *Rotating electrical machines – Part 2: Methods for determining losses and efficiency of rotating electrical machinery from tests (excluding machines for traction vehicles)*

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 60034-17:2006, *Rotating electrical machines – Part 17: Cage induction motors when fed from converters – Application guide*

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

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

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*

IEC 61800-5-2, *Adjustable speed electrical power drive systems – Part 5-2: Safety requirements – Functional*[1]

3 Terms and definitions

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

Table 1 provides an alphabetical cross-reference of terms.

Table 1 – Alphabetical list of terms

Term	Term number	Term	Term number	Term	Term number
bearing voltage ratio (BVR)	3.1	electromagnetic compatibility (EMC)	3.5	protective earthing	3.9
bonding	3.2	field weakening	3.6	skip band	3.10
common mode voltage (current)	3.3	peak rise time	3.7	surface transfer impedance	3.11
converter	3.4	power drive system (PDS)	3.8		

NOTE Throughout this technical specification, references to the following definitions are identified by italic script.

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 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).

3.3
common mode voltage (current)
arithmetic mean of the phase voltages (currents) to earth

3.4
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
[IEC 61800-2, 2.2.1, modified]

NOTE This definition is taken from IEC 61800-2 and, for the purposes of this technical specification, embraces the terms complete drive module (CDM) and basic drive module (BDM) as used in the IEC 61800 series.

_____

[1] To be published.

3.5
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 [IEV 161-01-07]

3.6
field weakening
motor operating mode where motor flux is less than the flux corresponding to the motor rating

3.7
peak rise time
time interval between the 10 % and 90 % points of the zero-to-peak voltage (see Figure 11)

3.8
power drive system
PDS
system consisting of power equipment (composed of *converter* section, a.c. 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.)

3.9
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, modified]

3.10
skip band
small band of operating frequencies where steady-state operation of the *PDS* is inhibited

3.11
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 entire 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);

- the duty cycle of the application (a continuous process or a combination of starts, stops, and speed changes; see 3.1 of 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 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 *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 motors, 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 motor 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 4.3.7).

4.3.2   Torque/speed capability

Figure 1 shows the torque/speed capability of *converter*-fed 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 $1/n$. For induction motors, 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 motors, 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.

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

In some applications, it may be possible to apply a short-time torque boost for starting.
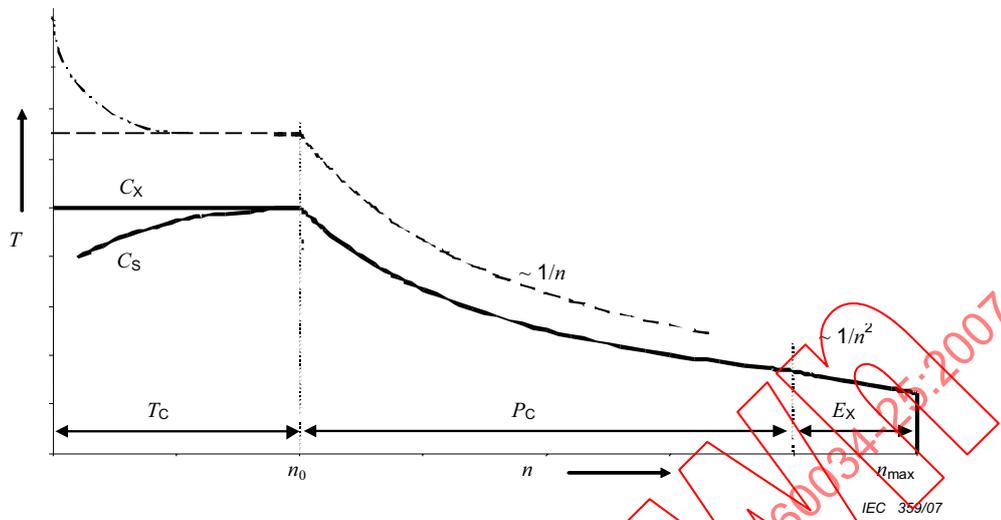
Key

———— 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 motors)

Figure 1 – Torque/speed capability

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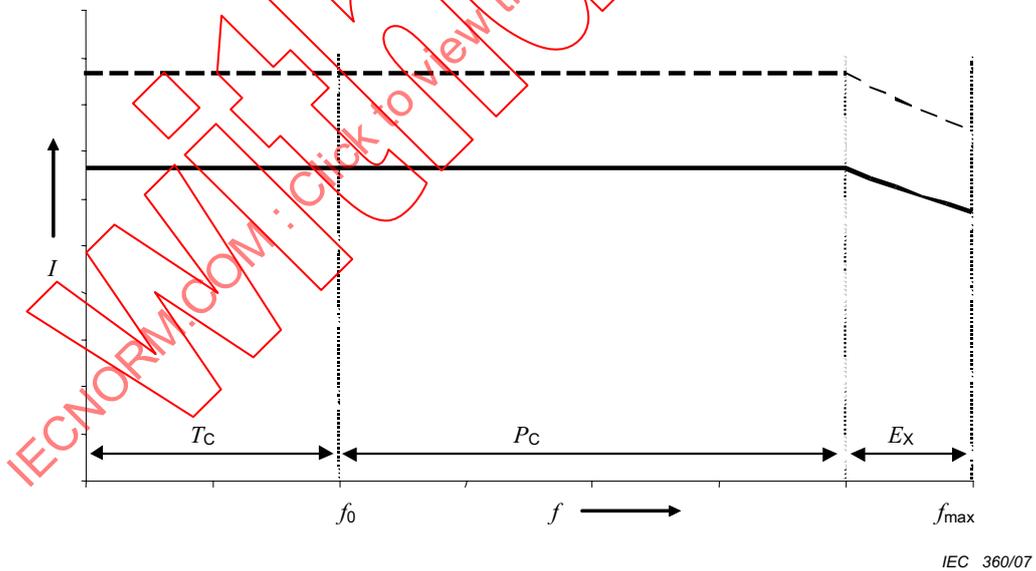
Figure 2 – *Converter* output current

4.3.3 Limiting factors on torque/speed capability

The significant factors which influence the torque/speed capability are shown in Table 2.

Table 2 – Significant factors affecting torque/speed capability

Condition	Motor	*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

4.3.4 Overspeed capability

As specified in IEC 60034-1, the overspeed of a.c. machines is fixed to 1,2 times the maximum rated speed, but an overspeed 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 motor 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 motors, an acceleration to a speed higher than the maximum operational speed determined in the control of the *converter* is impossible. Especially for large 'super synchronous' motors, it is often beneficial for the overall design to limit the test overspeed to 1,05 times the maximum operation speed. There is no technically justified argument against such agreement.

NOTE 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.

4.3.5 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 have often 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 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.

4.3.6 Voltage/frequency characteristics

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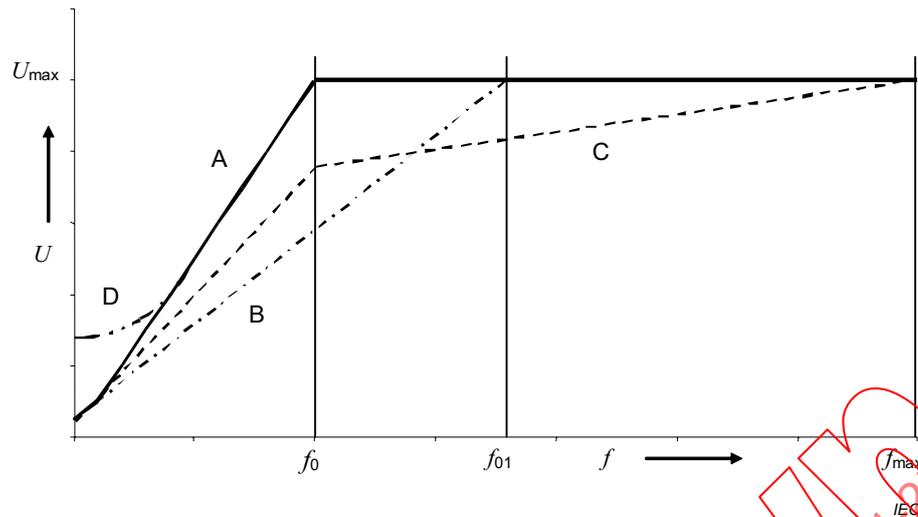
Key

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

Figure 3 – *Converter* output voltage/frequency characteristics

4.3.7   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.

4.3.8   Duty cycles

4.3.8.1   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 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 d.c. 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*.

4.3.8.2   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   Motor requirements

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

Table 3 indicates some main individual aspects and design considerations.

Table 3 – 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). *U/f* characteristic is constant until $f > f_0$ (see Figure 3)
Improved motor efficiency with *converter* supply	Rotor cage designs (rotor bars with low current displacement are preferred, see 5.2). May adversely affect line starting 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 % to 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 electrical parameters of the motor equivalent circuit (see Table 4 for examples) may be requested from the motor designer for tuning the *converter*.

Table 4 – 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 for induction motors			
Stator resistance (R_s)	At operating temperature	Optional for IR compensation	Yes
Rotor resistance (see NOTE) (R_r')	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 (see NOTE) $(X_{\sigma r}')$	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		Optional	Optional
NOTE The rotor electrical parameters R_r' and $X_{\sigma r}'$ are as referred to the stator circuit.			

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 (for induction motors fed from U-*converters*)

5.1   General

U-*converters* impress their output voltage on the associated motors. The output voltage synthesizes a sinusoidal wave using quasi-rectangular voltage pulses, having steep slopes and approximately constant amplitude (two-level *converters* impress a peak-to-peak value of the intermediate d.c. 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 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 for two-level *converters* and thus up to about 1 % to 2 % of the rated output of the motor, decreasing with increasing motor size. For three-level *converters*, the additional losses due to *converter* supply are lower, typically 0,2 % to 1 % of rated output.

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

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

For the *converter* output pulses the motor 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).

Experience has shown that the additional losses due to *converter* supply are independent of load. The influence of saturation (due to flux or to current) is small, and the additional losses due to *converter* supply can be minimized by various design measures, for example:

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

5.3   *Converter* features to reduce the motor losses

5.3.1   Reduction of fundamental losses

Figure 4 shows examples of the losses at no-load and at full-load for a 37 kW, 50 Hz motor powered from sinusoidal and 5,5 kHz U-*converter* supplies. It can be seen that the additional losses due to PWM supply are small compared with the fundamental losses.

IEC   362/07
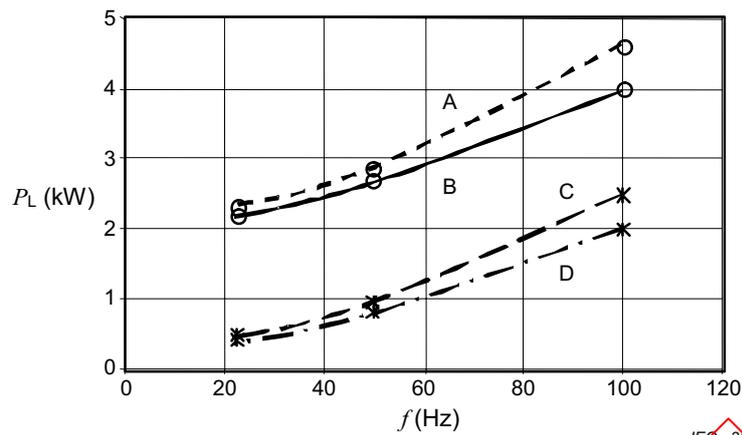
Key

A Full load, PWM supply   B Full-load, sine supply   C No load, PWM supply   D No load, sine supply

Figure 4 – 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 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. 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 motor.

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 motor flux according to the need so that the motor current power factor stays at the optimum value.

The fundamental losses may also be reduced by variation of the intermediate d.c. voltage.

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 motor show a strong decline with increasing pulse frequency up to a few kHz (see Figure 5). 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.
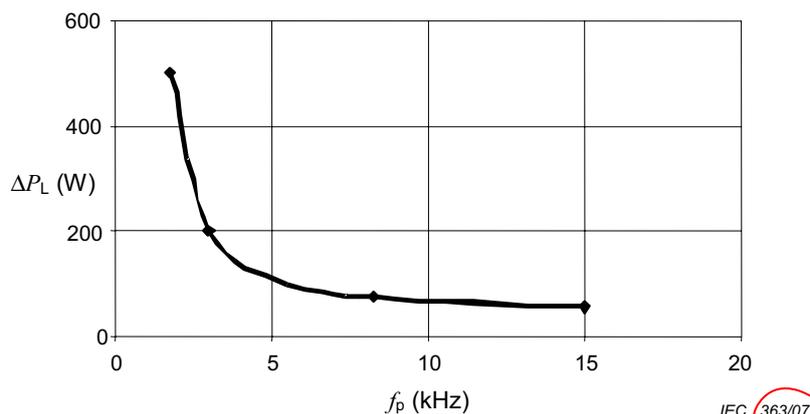
Figure 5 – Additional losses ΔP_L of a motor (same motor as Figure 4) due to *converter* supply, as a function of pulse frequency f_p, at 50 Hz rotational frequency

5.4 Use of filters to reduce additional motor 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 motor terminals. The total effects will depend on the application and dimensioning of the motor and the filter. The voltage drop across the filter will reduce the voltage at the motor terminals, and this should be taken into account in order to avoid an increase in the fundamental current loss in the motor. Also, there will be some losses in the filter, but these will generally be lower than the reduction of additional motor losses due to *converter* supply, and so the overall efficiency of the *PDS* will improve.

In addition to reducing the additional motor losses due to *converter* supply, such filters may also have a beneficial effect in reduced voltage stress on the motor 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 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 class (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. The most suitable duty types for *converter*-fed motors 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, 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 IEC 60034-2, but there is not yet a standard procedure for motors fed from *converters*. When required, the motor efficiency shall be measured on a sinusoidal power supply at rated frequency, unless otherwise specified by mutual agreement between the manufacturer and the user. For motors of power higher than 150 kW, the summation-of-losses method is preferred.

If practicable, to achieve an accurate assessment of the no-load losses (including the additional losses), they should be measured at the same pulse pattern and pulse frequency that the *converter* will produce at rated load.

6   Noise, vibration and torsional oscillation

6.1   Noise

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 and radial excitations of the stator core 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 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 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 6 (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
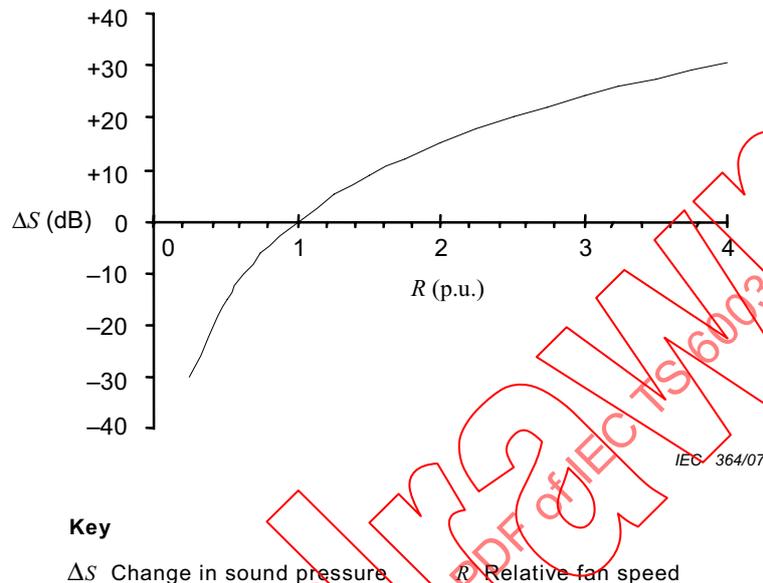
Figure 6 – Fan noise as a function of fan speed

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 U-*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 (see Figure A.2). The resonance frequencies for the modes $r = 0$ and $r = 2p$ (see Figure 7 for illustrations of modes $r = 0$, 2 and 4) 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.

r = 0   r = 2   r = 4
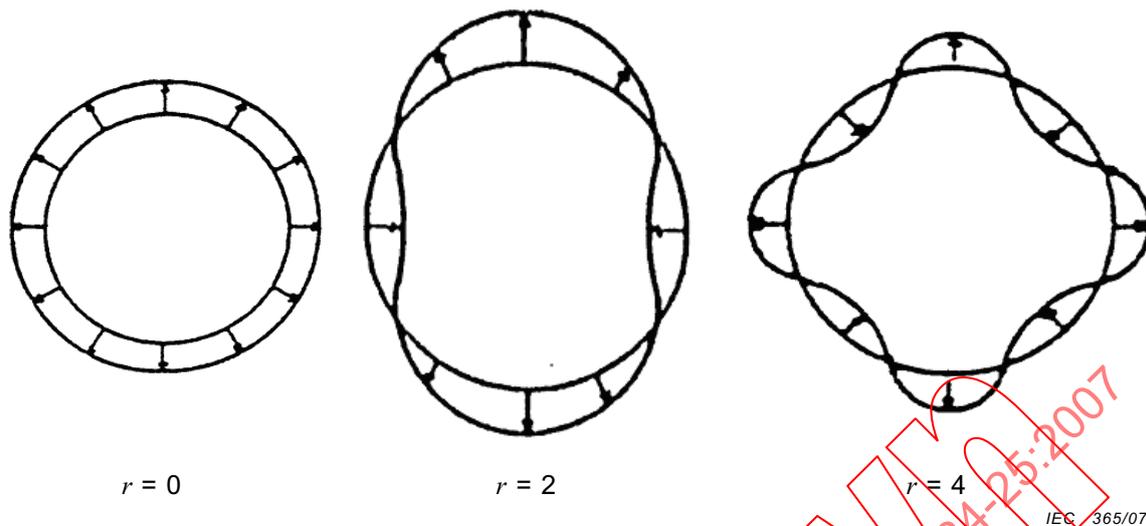
Figure 7 – Vibration modes

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.

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

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 (but see 6.1.4.2).

6.1.4.2 Test conditions

It is preferred that the motor should be rigidly mounted to a surface representative of the installed operating condition, and, if practicable, tests should be made with the motor supplied from a *converter* with the output characteristics that will be used in the application.

Ideally, for a full characterization of the overall performance, a preliminary measurement may be made over the entire speed range to determine the conditions for maximum noise, and a final measurement made under these conditions.

Alternatively, by agreement between manufacturer and customer, tests may be carried out at no load and a single speed, using a *converter* or sinusoidal supply.

6.1.4.3 Sound power level limits

Sound power level limits are specified in IEC 60034-9, in which Clause 7 shows as a table the expected increments of level of *converter*-fed motors compared with sinusoidal supply.

This table is reproduced as Annex C of this specification.

6.2 Vibration (excluding torsional oscillation)

6.2.1 General

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

- the electromagnetic design of the motor;

- the motor structure, particularly the frame assembly;

- the motor mounting;

- shaft stiffness;

- the rigidity of the coupling between the motor 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 motor and its mounting, similar vibration levels to that produced by a motor operating on a sinusoidal supply will be obtained. Thus, for motors supplied from PWM U-*converters*, there is no need to establish vibration levels that are different from the figures for sinusoidal supplied motors given in IEC 60034-14.

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

For a motor coupled to a driven equipment there are many natural resonances and if the application requires the motor 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 programme the controller so that the frequency bands that are exciting the mechanical resonances are "skipped" (see 4.3.7).

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 motor 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 (but see 6.2.2.2).

6.2.2.2 Test conditions

It is preferred that the motor should be rigidly mounted to a surface representative of the installed operating condition and, if practicable, tests should be made with the motor supplied from a *converter* with the pulse frequency and pattern that will be used in the application.

Ideally, for a full characterization of the overall performance, a preliminary measurement may be made over the entire speed and load range (see note 1) to determine the conditions for maximum vibration, and a final measurement made under these conditions.

Alternatively, by agreement between manufacturer and customer, tests may be carried out at no load and a single speed, using a *converter* or sinusoidal supply.

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.

6.2.2.3   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 Table 1 of IEC 60034-14.

6.3   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.

For PWM U-*converters* with pulse frequencies greater than 2 kHz, the significant oscillating torques at 6 and 12 times fundamental frequency are always less than 10 % of rated torque.

A d.c. 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 d.c., 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   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 a.c. sinusoidal source.

7.2   Causes

A U-*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 d.c. bus voltage (1 p.u.). This level depends on the rectified mains voltage or braking voltage level or power factor correction regulation voltage.

Modern low voltage *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 8 shows a plot of the surge count at the terminals of a motor 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 *peak rise time* and magnitude. However, the risk of insulation damage (due to partial discharge, see 7.3 and 7.4) is more severe with surges of fast rise time and high voltage, which indicates that surges in the right-hand portion of this diagram are more significant.
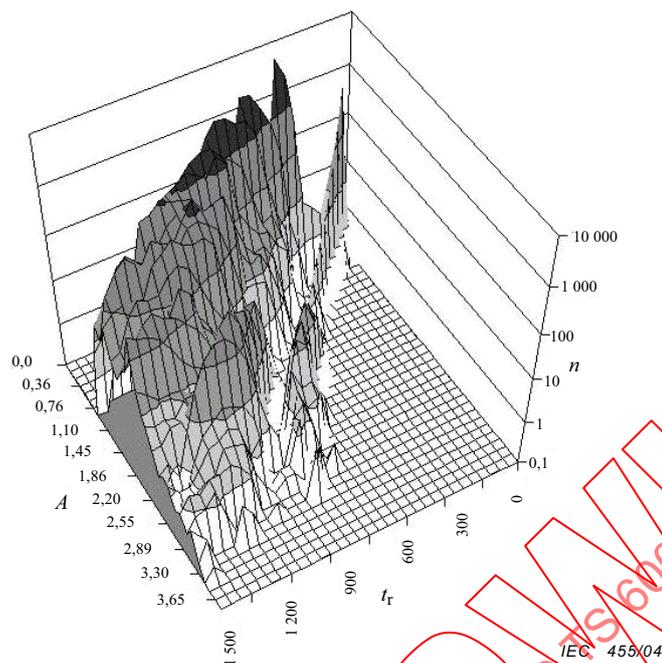
Key

A Surge magnitude (p.u.)   *t*_r Peak rise time (ns)   *n* Surge count (per second)

Figure 8 – 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. phase-to-phase and phase-to-ground). These voltage overshoots are created by reflected waves at the interface between cable and motor terminals due to impedance mismatch, and depend on the *converter* output, the cable length between the *converter* and the motor and motor 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 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 9 with an enlarged view of one surge shown in Figure 10.

Key
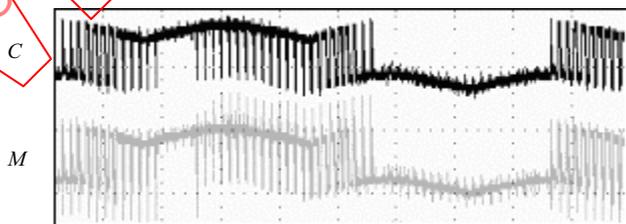
C Phase voltage at *converter*   *M* Phase voltage at motor

**Figure 9 – Typical voltage surges on one phase at the *converter*
and at the motor terminals (2 ms/division)**

Key

C Phase voltage at *converter*   *M* Phase voltage at motor

IEC   457/04
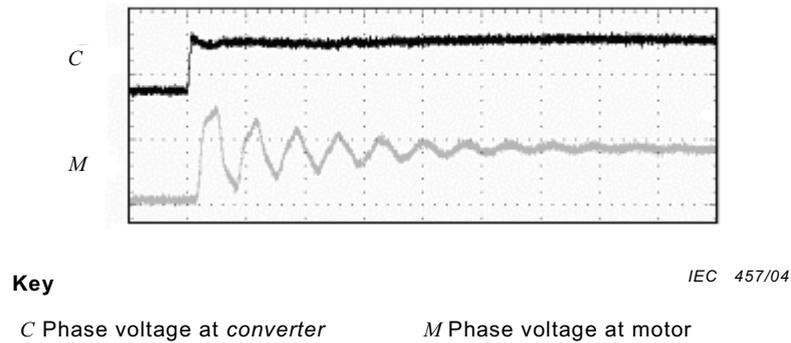
Figure 10 – Individual short rise time surge from Figure 9 (1 µs/division)

As the cable length increases, the pulse overshoot generally increases to a maximum then declines. Meanwhile, the *peak 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 *peak rise time* at the motor terminals is determined mainly by the cable characteristics and the impedance mismatch between the cable and the motor, 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) or by multiple reflections as follows.

- Double transition occurs, for example, when one phase switches from minus to plus d.c. 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 the time between two pulses is matched with the propagation time between the *converter* and the motor, an over-voltage greater than 2 p.u. can be generated at the motor terminals.
- Where the cable consists of several sections, reflections will occur at each impedance mismatch, and so special care should be taken.

7.3   Winding electrical stress

The dielectric stress of the winding insulation is determined by the peak voltage and the *peak rise time* (for definition, see Figure 11) of the impulse at the motor terminals, and on the frequency of the impulses produced by the *converter*.
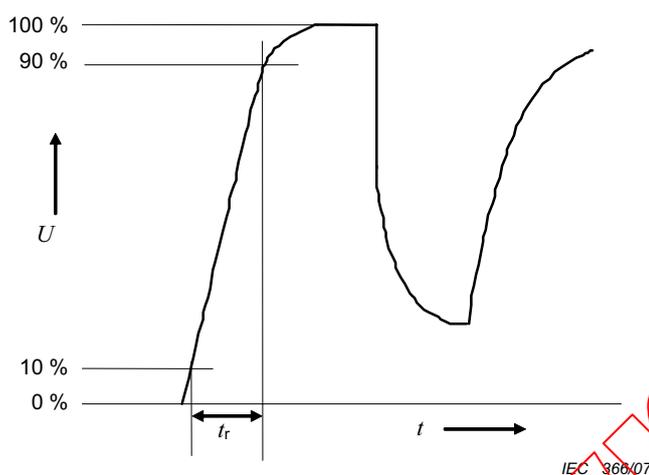
Figure 11 – Definition of the *peak rise time* t_r of the voltage at the motor terminals

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 *peak 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 12 shows an example of the distribution of the voltage across a 50-turn form-wound coil as a function of the *peak rise time*. As illustrated, the shorter the *peak rise time*, the more voltage appears across the first turn of the coil.

Key
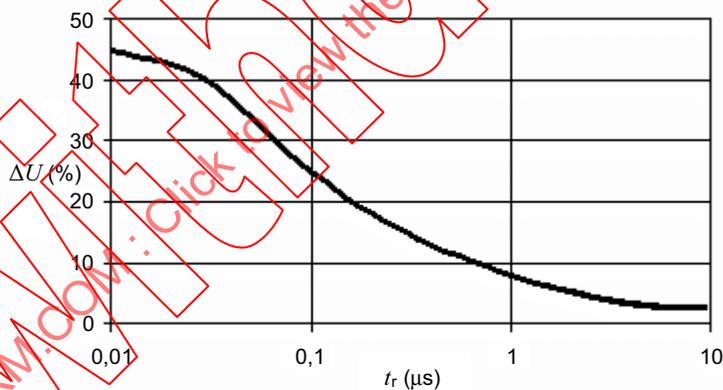
ΔU　Voltage across the first turn (% of line-to-ground voltage)　　　t_r　*Peak rise time*

Figure 12 – First turn voltage as a function of the *peak 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 *peak 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);

- environment atmosphere (composition and pressure);

- condition of the insulation (contamination by dirt or humidity, etc.).

Figure 13 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.
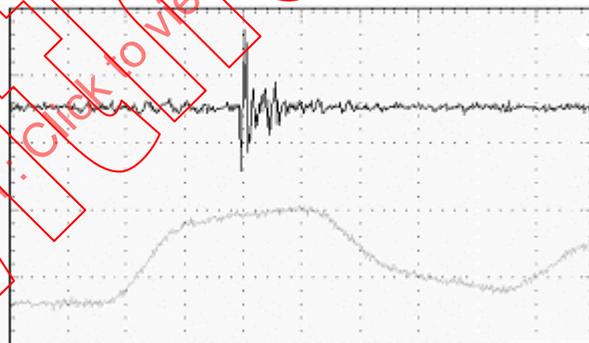
IEC   460/04

Key

S Voltage surge at motor terminals   *D* Discharge pulse

Figure 13 – Discharge pulse occurring as a result of *converter* generated voltage surge at motor terminals (100 ns/division)

7.5   Responsibilities

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, earthing, etc. Relevant parameters for insulation stress are: transient peak voltage values, *peak 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.

Figure 14 shows the impulse voltage for the phase-to-phase insulation for motors fed from *converters* having passive (diode bridge) rectifier stages, where the d.c. link voltage can not be increased by regenerative operation.

Key

A Without filters for motors up to 500 V a.c.

B Without filters for motors up to 690 V a.c.

* Examples of measured results at 415 V supply, for different lengths of steel armoured cable
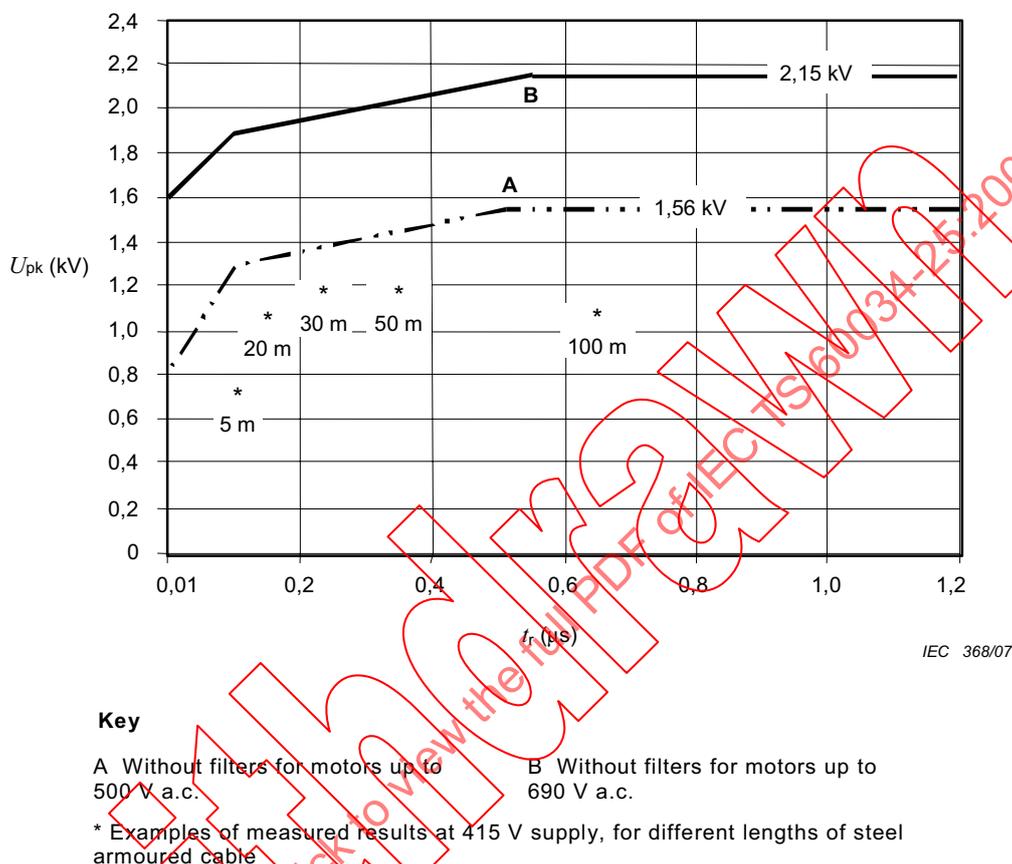
Figure 14 – Limiting curves of impulse voltage U_{pk}, measured between two motor phase terminals, as a function of the *peak rise time* t_r

The phase-to-ground insulation stress can be influenced by the *PDS* earthing configuration. If the d.c. link is effectively floating with respect to ground, this stress can be up to twice that of the phase-to-phase value.

7.6 *Converter* characteristics

The amplitude of the output voltage pulses is in general the d.c. 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 *peak 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 *peak rise time* referred to in Figure 14 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 *peak 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. Some of these, together with their effects, are listed below.

- Although it is often difficult or impractical, changing the cable length and/or earthing 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 (for example, 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.

- Changing the earthing configuration if phase-to-ground problems occur.

- Installing an output reactor (see 9.2.2) will increase the *peak rise time* and decrease the peak voltage 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 *PDS* design.

- Installing an output du/dt filter (see 9.2.3) between the *converter* and the cable leading to the motor will significantly increase the *peak 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 *peak rise time*. The possibility of using this solution depends on the required characteristics, particularly the speed range and dynamic performance, of the application. A type 1) filter will reduce both phase-phase and phase-earth voltage stresses, while a type 2) filter will only reduce the phase-phase voltage stresses. In addition, such a filter will reduce *EMC* interference and additional motor losses and noise. Also, with a type 1) filter, standard unscreened cables can be used.

- 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, two impulse withstand levels are available for low voltage induction motors as follows.

- Withstand level according to curve A in Figure 14

  When using *converters* without any reduction methods as described in 7.7, such motors are suitable for *PDS* up to 500 V a.c. 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 14

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

NOTE   IEC 60034-17, which concerns the *converter* supply of motors designed for sinusoidal supply, contains another withstand level. This has been derived using different assumptions from those used in deriving curves A and B, and is not directly comparable with those curves.

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 a.c. flux (ring flux) in the yoke. This induces an a.c. 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 earthing 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 earthing, and capacitive discharge.

Two types of bearing currents, high-frequency circulating current (I_C) and shaft earthing current (I_S), are shown schematically in Figure 15. These are strongly influenced by the earthing arrangements and earthing impedances.

Key

D *Converter*   M Motor   C Shaft coupling   L Driven load

U_{CM} HF *common mode voltage*

$\wedge$ I_{CM} HF *common mode current* $\wedge$ U_S HF shaft voltage $\wedge$ I_C HF circulating current

$\wedge$ I_{PE} HF return current $\wedge$ U_F HF frame voltage $\wedge$ I_S HF shaft current

Figure 15 – 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 earthing 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 d.c. 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 d.c. 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 16) 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 d.c. link voltage level.
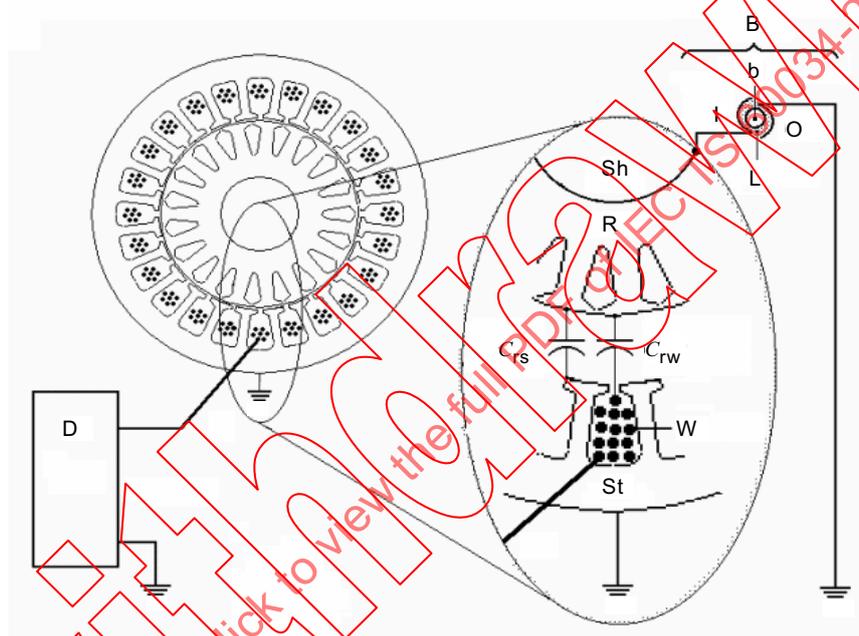
IEC   463/04

Key

D Converter	Sh Shaft	R Rotor	St Stator
W Winding	C_{rs} Rotor-stator capacitance	C_{rw} Rotor-winding capacitance	B Bearing
b Ball or roller	I Inner race	O Outer race	L Lubricant film

Figure 16 – 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 17 and Figure 18 show typical bearing damage due to *common mode currents* and electrical discharge.
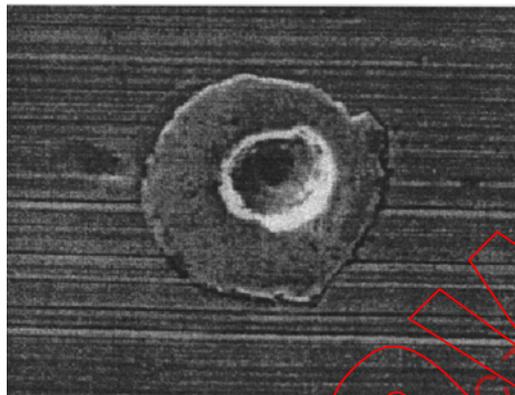
IEC   464/04

Figure 17 – Bearing pitting due to electrical discharge (pit diameter 30 µm to 50 µm)
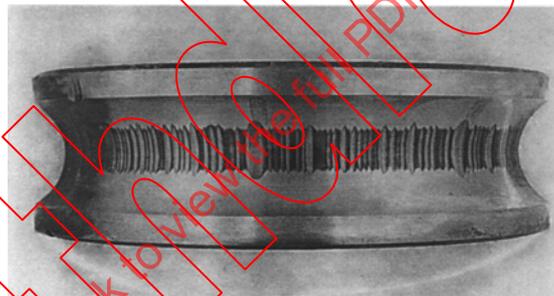
IEC   465/04

Figure 18 – 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 earthing 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 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 at the high *common mode current* frequencies, if the installation follows the principles of 8.6.3.

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 du/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 earthing 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 earthing 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

Table 5 – Effectiveness of bearing current countermeasures *(continued)*

Counter measure	Current type			Additional comments
	Circulating currents (8.1.2, 8.2.2)	Shaft earthing currents (8.2.3)	Capacitive discharge currents (8.2.4)	
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
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.				

8.6.3 Other factors and features influencing the bearing currents

- Large physical size or high output power of the machine tends to increase the induced shaft voltage.

- The physical shape of the motor also has an effect on the induced shaft voltage: short and fat shape is generally better than long and thin 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 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-motors supplied by U-*converters* in the rotor circuit require special attention because the *bearing voltage ratio* (*BVR*) is much higher (*BVR* ≈ 1) than in stator-fed motors.

8.7 Additional considerations for motors fed by high voltage U-*converters*

8.7.1 General

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

- High-voltage 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 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 *converters*, 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 motors is in the same range as in low-voltage motors).

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

The high-voltage in the *converter* intermediate circuit and the physical size of the motor emphasize to protect the bearings. Use insulated bearing structure for both bearings or one insulated (NDE) bearing and a shaft earthing brush at the DE bearing or an effective *common mode* filter at the *converter* output (see Table 5).

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

As the motor already has slip rings and brushes additional shaft earthing brushes in both ends will protect the bearings. Alternatively, another applicable method from Table 5 may be selected.

NOTE If the U-*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.

8.8 Bearing current protection for motors fed by high-voltage current-source *converters* (I-*converters*)

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-machines supplied by I-*converters* 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 motor 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 motor 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 7.5).

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 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 earthing 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 earthing. 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 19).

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

IEC   466/04
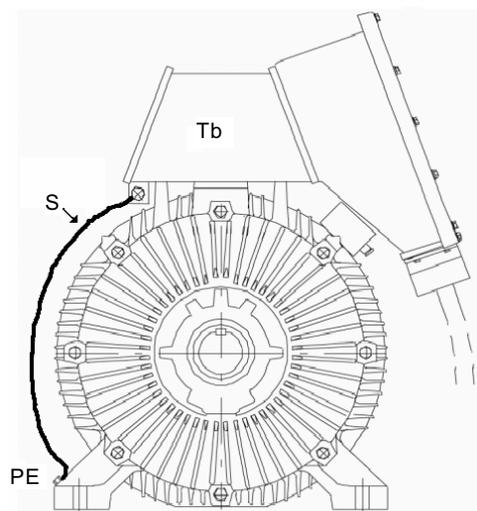
Key

Tb Terminal box   PE Connection to motor frame   S *Bonding* strap

Figure 19 – *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. 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 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 20 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 20 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* may be satisfactory.

- three-core cable with a steel or galvanized iron, low pitch, stranded armour/shield (see Figure 20 C). If the shield has an insufficient cross-section for use as a protective conductor, a separate earthing conductor is needed.
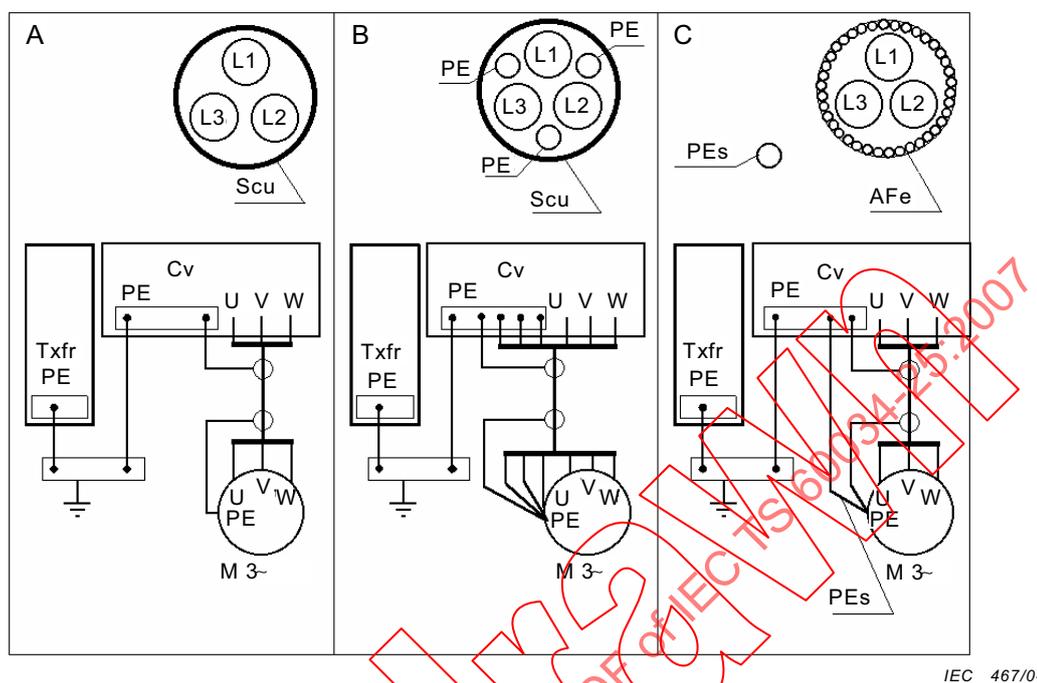
IEC   467/04

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

Figure 20 – 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 earthing.

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 21.
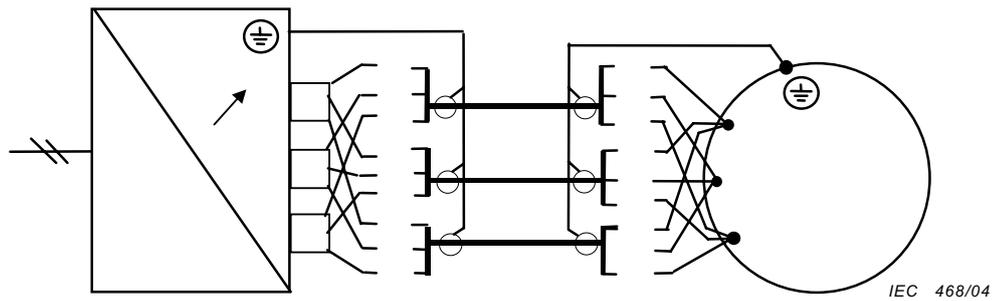
Figure 21 – Parallel symmetrical cabling of high-power *converter* and motor

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 d.c. 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 22 and Figure 23 respectively.
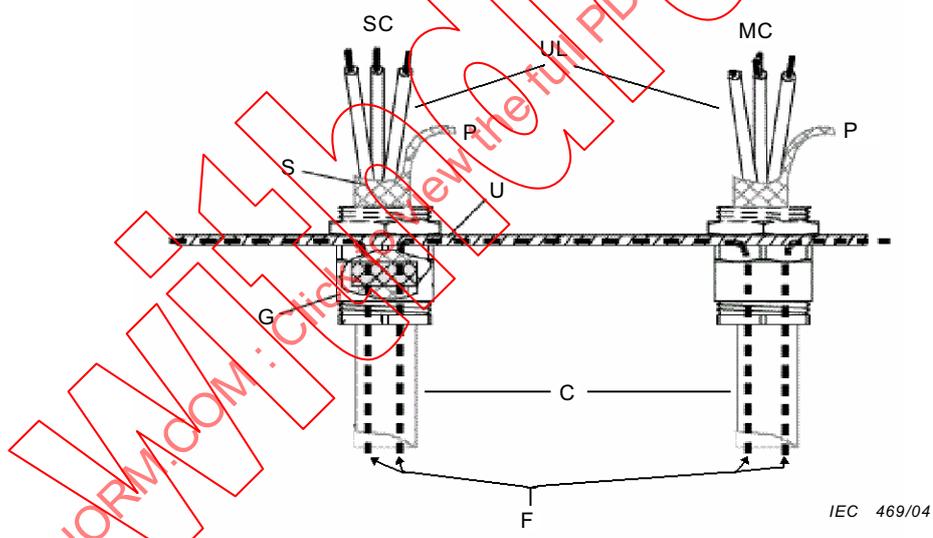
Key

SC Supply cable	MC Motor 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 22 – *Converter* connections with 360º HF cable glands
showing the Faraday cage**
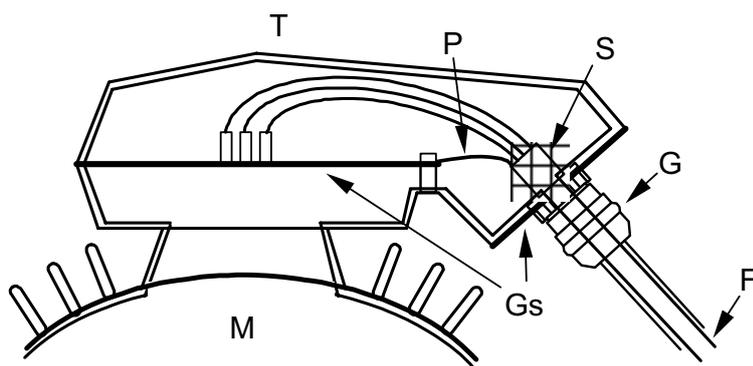
Key

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

Figure 23 – Motor end termination with 360° connection

The shield connections at the motor terminal box should be made with either an *EMC* cable gland as shown in Figure 24a or with a shield clamp as shown in Figure 24b. Similar connections are required at the *converter* enclosure.
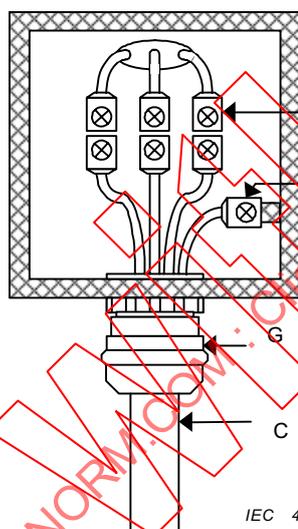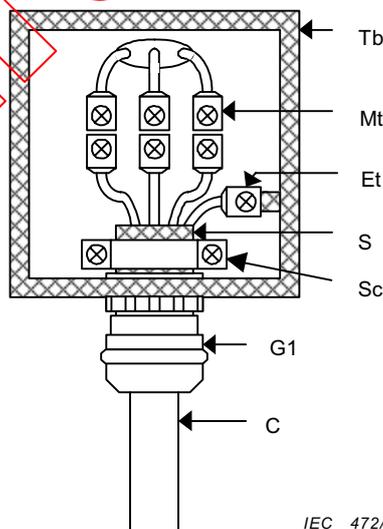
Key

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

Figure 24a – Gland connection   **Figure 24b – Clamp connection**

Figure 24 – Cable shield connection

9.1.4.4   Cabling and earthing of auxiliary devices

Auxiliary devices, such as tachometers, should be electrically insulated from the motor 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 motor, 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 motor 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 25a, the addition of the reactor has increased the *peak 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 motor 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 *peak rise time*. In the example shown in Figure 25b, the peak voltage is reduced to 684 V with a du/dt of 40 V/µs. Some increased losses of 0,5 % – 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 motor becomes sinusoidal. The phase-to-phase output voltage (differential) for approximately 1,5 periods of the switching frequency is shown in Figure 25c. Generally, there are the following two types of sinusoidal filters.

1) Design with both phase-to-ground and phase-to-phase filtering.
2) Design with only phase-to-phase filtering.

These filters are expensive and have also other limitations. They prevent the motor 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   Motor termination unit

A motor termination unit can be connected at the motor terminals. Its purpose is to match the motor impedance to that of the cable, thereby preventing voltage reflections at the motor. For the example illustrated in Figure 25d the peak voltage is now only 800 V with a *peak rise time* of 2 μs. Typically, these filters add around 0,5 % – 1,0 % losses.
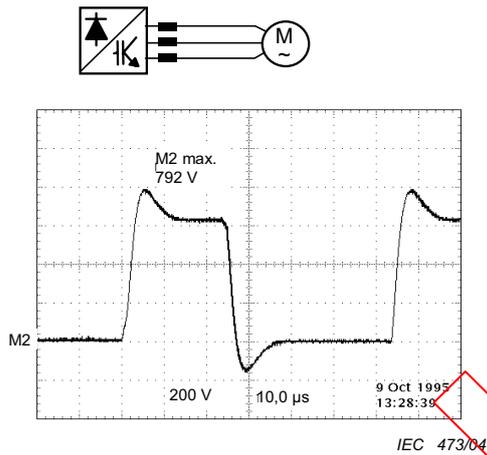
Figure 25a – Output reactor (3 %)   **Figure 25b – Output du/dt filter**
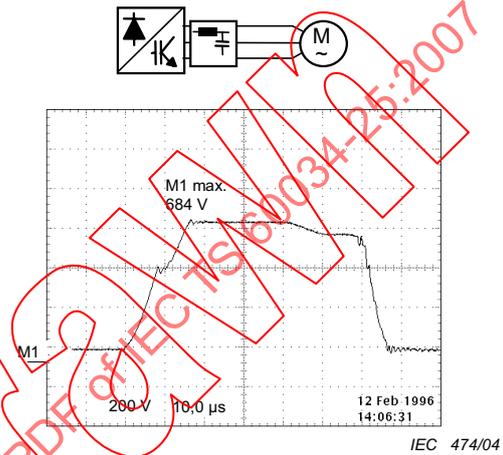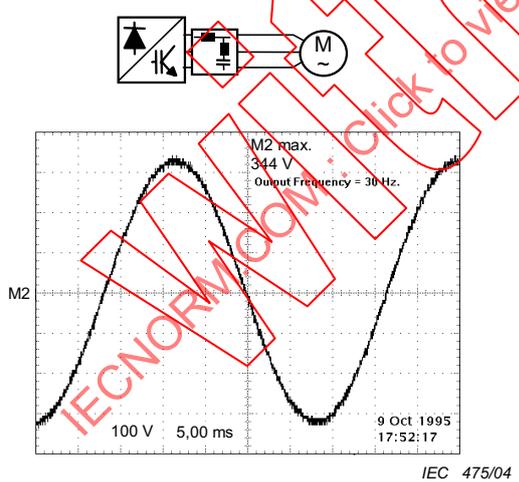
Figure 25c – Sinusoidal filter   **Figure 25d – Motor termination unit**
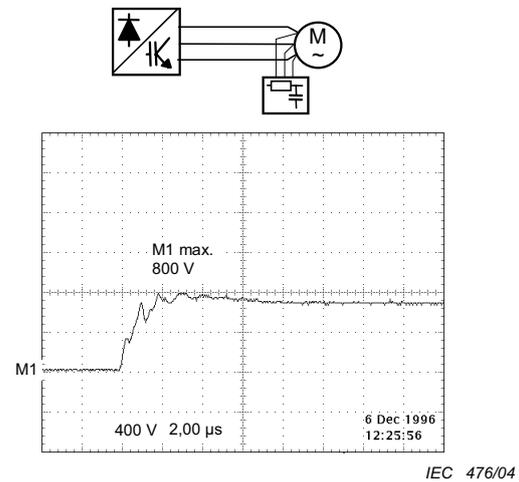
Figure 25 – Characteristics of preventative measures

9.3   Integral motors (integrated motor and drive modules)

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

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 bearing current risks;

- no long cables or leads between the *converter* and the motor keep the voltage reflections and insulation stresses low;

- compact solution --- savings in total required space and installation;

- a single supplier --- clear responsibility.

But it has some disadvantages too:

- depending on the application the environment may be very hostile for the *converter* electronics (high degree of enclosure required and shock and heat/cold resistant circuit boards and components);

- the technical life of the main components may differ significantly (motors some 15 to 20 years but *converters* only 5 to 10 years).

10 Additional considerations for permanent magnet (PM) synchronous motors fed by U-*converters*

10.1 System characteristics

The benefits of a *PDS* consisting of a U-*converter* and a permanent magnet synchronous motor instead of an induction motor are:

- lower VA rating of the *converter*, as a synchronous motor can be rated for unity power factor;

- better efficiency of motor and *converter*;

- reduced motor size, compared with an induction motor of the same rating;

- in a properly designed motor, the rotor losses are minimal and therefore will have no effect on the thermal behaviour of the rotor;

- simpler cooling arrangements of the motor, 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 motors 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 Motor insulation electrical stresses

The statements of Clause 7 remain valid.

When the motor is operating in regenerating mode, the back EMF will generate a voltage at the motor terminals. This should not be permitted to exceed the capability of the *converter* d.c. link.

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 demagnetization, as well as being caused by additional heating (see 10.2), can also be caused if the motor terminals are short-circuited while the motor is rotating.

11 Additional considerations for cage induction motors fed by high voltage U-*converters*

11.1 General

In general, the statements made with respect to low-voltage motors supplied by U-*converters* are valid for medium-voltage motors and *converters* as well. Nevertheless, some differences exist.

11.2 System characteristics

IEC   370/07

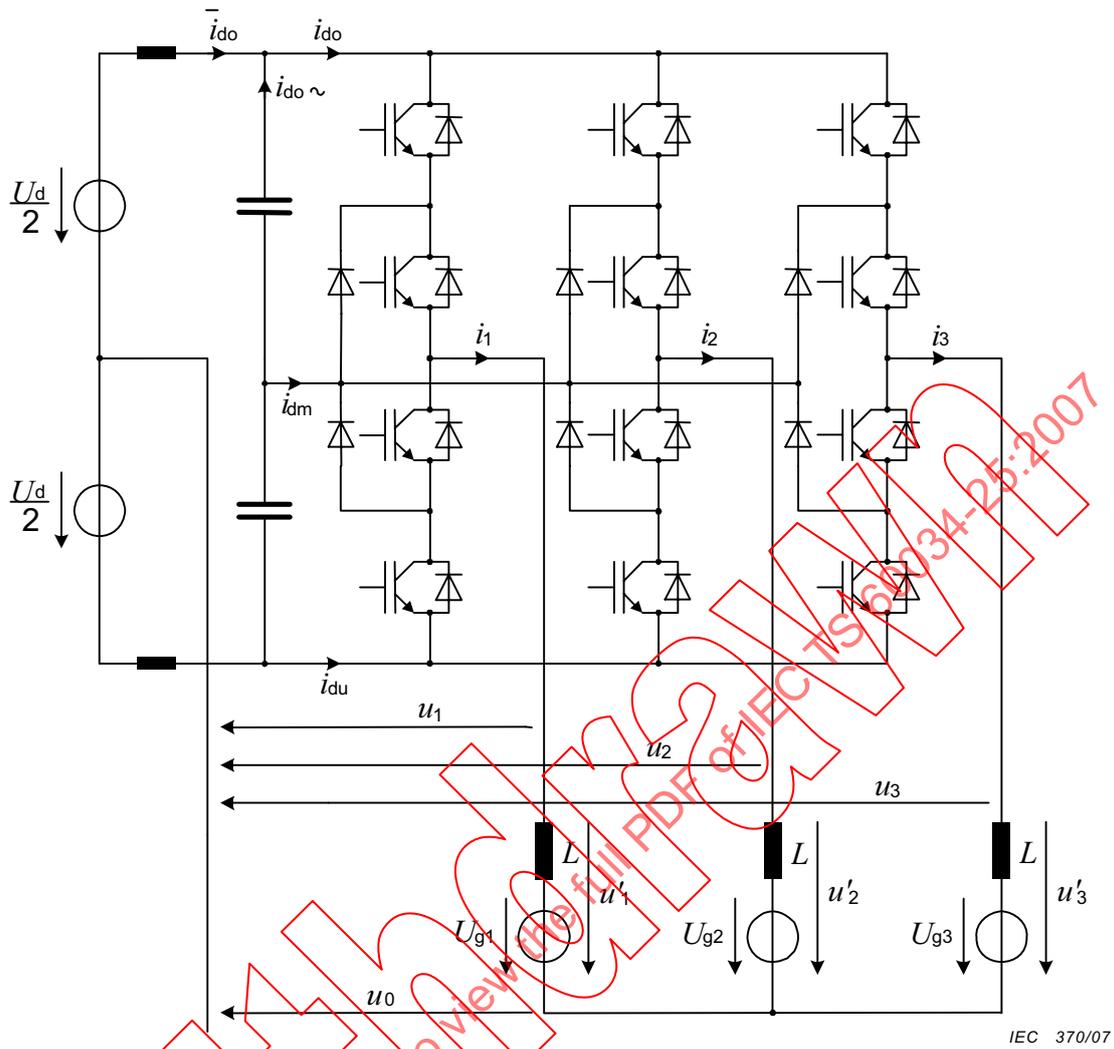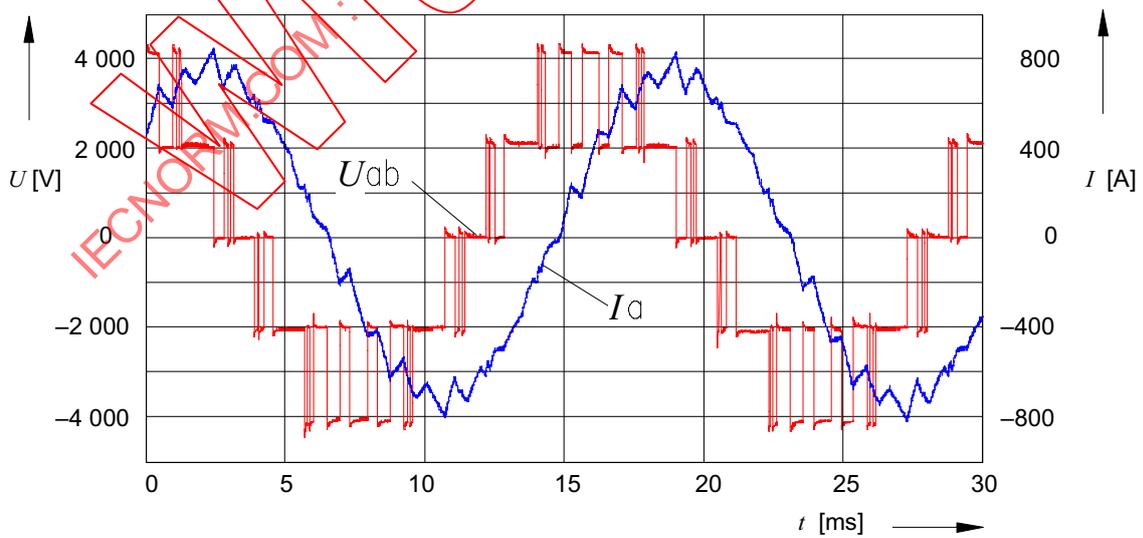**Figure 26 – Schematic of typical three-level *converter***

IEC   371/07

Figure 27 – Output voltage and current from typical three-level *converter*

Medium voltage *converters* are three-level or multi-level *converters*, which means that they have more than one IGBT or IGCT in each branch of the inverter bridge connected in series. For a three-level *converter*, for example, the line-to-line voltage can be impressed in 5 different values (–Ud, –½ Ud, 0, ½ Ud, Ud) instead of only 3 values (–Ud, 0, Ud) 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). 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 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 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 machines fed from U-*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 motor, a general statement is not possible.

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 must consider the main influencing factors like current displacement in stator and rotor windings.

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

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 machine supplied from a *converter*. If required, noise and vibration measurements of the complete *PDS* shall 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 operation 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 Motor 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. 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 *peak 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.
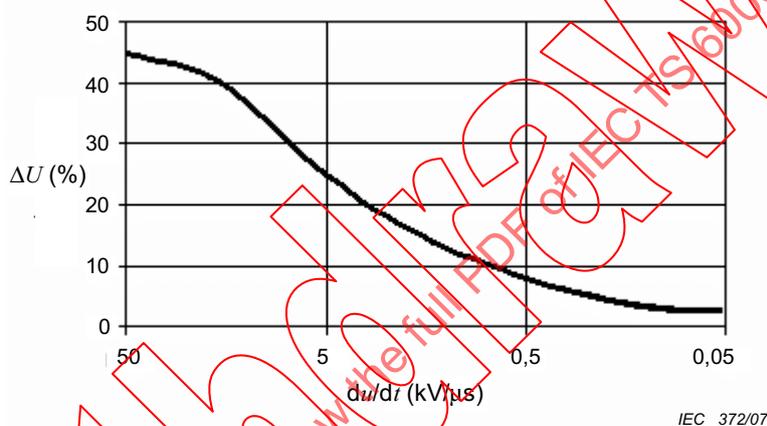
Figure 28 – Typical first turn voltage ΔU (as a percentage of the line-to-ground voltage) as a function of du/dt

11.5.2 Motor terminal overvoltage

In addition to the factors mentioned in 7.1 to 7.3, the overvoltage appearing at the terminals of a *converter*-fed motor also depends on the number of *converter* stages.

11.5.3 Stator winding voltage stresses in *converter* applications

11.5.3.1 General

Converter-fed motor 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 29.
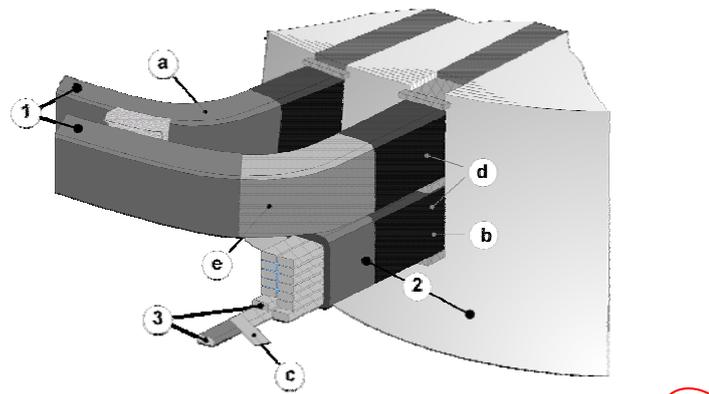
IEC 873/07

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 29 – 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 motor designer is aware of the characteristics of *converter* output voltage waveforms, as seen at the motor terminals, to ensure that these are taken account of 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 *peak rise times* in the order of 50 ns to 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 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 greater than about 3 kV/mm. This is more likely in *converter*-fed motors due to the higher transient repetitive voltages that appear on each phase. Appropriate end-winding spacing is required for *converter*-fed motors, 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 motors 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 29).

Care should be taken to avoid the possibility of the performance of this material being degraded by PD.

11.6 Bearing currents

The statements of Clause 8 remain valid.

12 Additional considerations for synchronous motors fed U-converters

12.1 System characteristics

The benefits of a *PDS* consisting of a U-*converter* and a synchronous motor instead of an induction motor are as follows.

- Lower VA rating of the *converter*, as a synchronous motor can be rated for unity power factor.
- Better efficiency of motor and *converter*.
- 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.

12.3 Noise, vibration and torsional oscillation

The statements of 11.4 remain valid.

12.4 Motor 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 motors fed by block-type I-*converters*
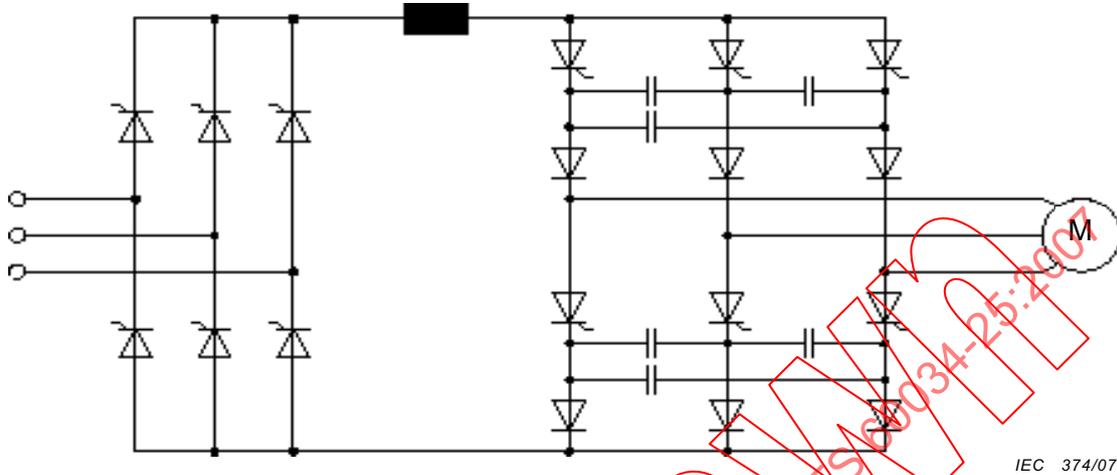
13.1 System characteristics

IEC 374/07

Figure 30 – Schematic of block-type I-*converter*

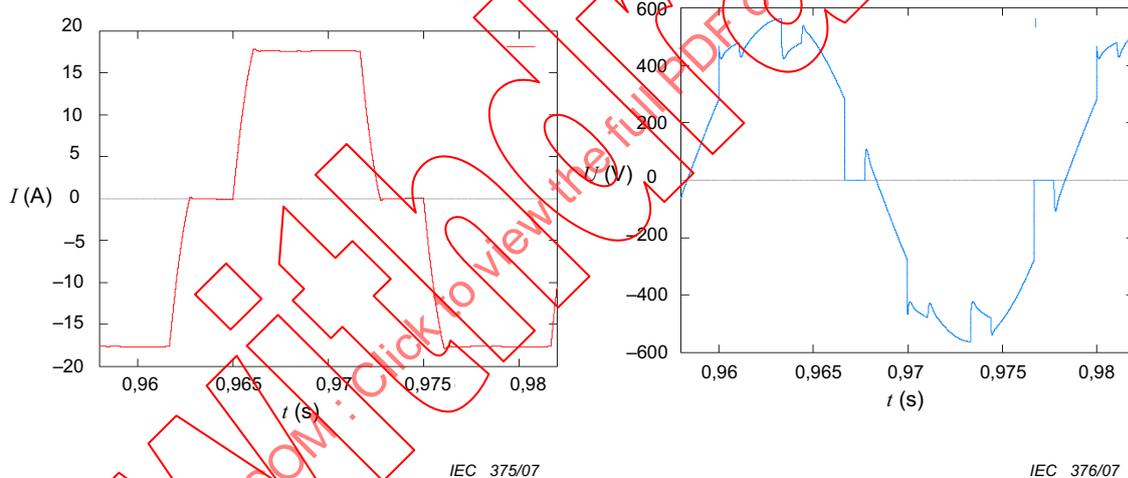IEC 375/07   IEC 376/07

Figure 31 – Current and voltage waveforms of block-type I-*converter*

The *converter* is characterized by

- a controlled, line-commutated inverter connected to the power supply;

- a large reactor in the intermediate circuit to smooth the d.c. current and;

- a controlled, self-commutated inverter connected to the motor.

The motor currents are block-type (120° blocks), containing harmonics of order n = –5; +7; -11; +13; … . 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 motor contains transients at all commutation intervals of the current.

The stator winding is part of the commutation circuit. Therefore, the motor should be designed for low leakage inductance; the *converter* manufacturer must 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 a motor supplied by an I-*converter* at full load, are typically higher than the extra losses of the same motor supplied by a PWM inverter (for details see Figure 4 of IEC 60034-17:2006). However, the overwhelming part of the extra losses decreases with decreasing load, whereas the extra losses of a motor supplied by a U-*converter* are independent of load. Therefore the difference between the extra losses of the two kinds of drives diminishes at partial load.

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 machines fed from I-*converters*. For strands of 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 machines fed from I-*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 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 fundamental 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 $f_r = (n \pm 1)f_1$ ($n = 1, 2, 3, \ldots$) 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 motor 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 I-*converters* on the performance of cage induction motors is the generation of pulsating torques of relatively high amplitudes. If the d.c. current in the intermediate current is smooth, the frequency of the pulsating torques is $(n-1)f_1$. The most significant frequency is $6f_1$, which will have an amplitude of approximately $0{,}1T_N$.

If the d.c. current ($I_{d.c.}$) contains ripples, additional pulsating torques at frequencies $(n-1)(g_1f_{mains} - g_2f_1)$, (where g_1, $g_2 = \pm1, \pm2, \ldots$), are generated, amongst them especially of the frequency $6(f_{mains} - f_1)$. The current ripple in the intermediate circuit $(i_{max} - i_{min})/i_{d.c.}$ 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 Motor insulation electrical stresses

As already stated in 13.1, the phase-voltage of the motor 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 *peak 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 I-*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 motors

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 I-*converters* 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 fundamental frequency exist. The frequencies of the pulsating torques follow the expression $12kf_1$ ($k = 1; 2;....$).

The equation of the frequencies of the pulsating torques, based on the d.c. current ripple, remains unchanged (see 13.3).

All statements of 13.1 to 13.5 regarding other effects of I-*converters* remain valid.

14 Additional considerations for synchronous motors fed by LCI

14.1 System characteristics

Synchronous motors with static or brushless excitation can also be supplied by I-*converters* (LCI). For the motor, this type of supply is the same as a block-type I-*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.

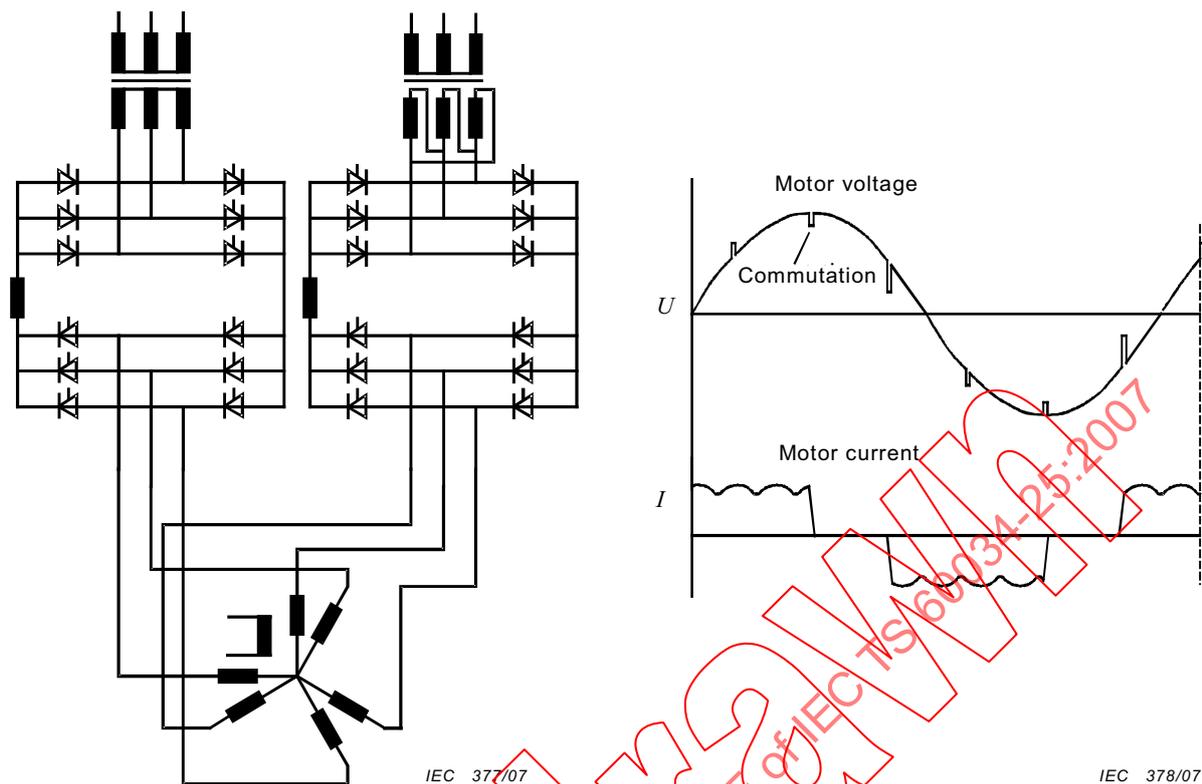The inverter connected to the power supply is line-commutated.

IEC   377/07

IEC   378/07

**Figure 32 – Schematic and voltage and current waveforms for a synchronous motor
supplied from an I-*converter***

The inverter connected to the motor is load-commutated. The synchronous 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 motor both the effective and the reactive power must be supplied by the *converter*. Therefore, the *converter* of a synchronous motor 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 machine can produce reactive power only when it is turning, not at standstill. Therefore, starting would be impossible without additional measures such as d.c. 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 32 can be regarded as two six-pulse I-*converters*, each feeding one of the motor'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 motor. This arrangement eliminates in the transformer the frequencies $-5f_1$, $+7f_1$, $-17f_1$, $+19f_1$, ... (reducing additional losses in the stator winding). In addition, this arrangement allows the possibility to synchronize the motor direct with the mains, in case speed adjustment is not required for some operation modes.

Motors with eight or more poles are commonly salient pole machines with laminated poles or pole shoes. A damper cage is incorporated in the pole shoes. For motors with four or six poles, a laminated cylindrical rotor, or a rotor with laminated or solid salient poles is common. Two-pole motors 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 motors with solid salient poles. Nevertheless, a general statement on the overall efficiency of both designs is not possible, since salient pole motors inherently have lower windage losses than motors with cylindrical rotor.