NEMA ICS 61800-4

ADJUSTABLE SPEED ELECTRICAL POWER DRIVE SYSTEMS

PART 4: GENERAL REQUIREMENTS — RATING SPECIFICATIONS FOR A.C. POWER DRIVE SYSTEMS ABOVE 1000 V A.C. AND NOT EXCEEDING 35 kV

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NEMA Standards Publication ICS 61800-4-2004

Adjustable Speed Electrical Power Drive Systems

Part 4: General Requirements—Rating Specifications for a.c. Power Drive Systems above 1000 V a.c. and Not Exceeding 35 kV

Published by:

National Electrical Manufacturers Association
1300 North 17th Street, Suite 1847
Rosslyn, Virginia 22209

www.nema.org

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Foreword

This document is an adaptation of the IEC Standard 61800-4 with the addition of requirements pertinent to use of these devices in the U.S. U.S. differences are indicated with (U.S. Differences) and italics.

1) The IEC (International Electrotechnical Commission) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of the 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, the IEC publishes International Standards. 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. The 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 the 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 National Committees.
3) The documents produced have the form of recommendations for international use and are published in the form of standards, technical specifications, technical reports or guides and they are accepted by the National Committees in that sense.
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International Standard IEC 61800-4 was prepared by IEC sub-committee 22G: Semiconductor power converters for adjustable speed electric drive systems, of IEC technical committee 22: Power electronic systems and equipment.

Annexes A, B and C are for information only.

The committee has decided that the contents of this publication will remain unchanged until 2008. At this date, the publication will be

- reconfirmed;
- withdrawn;
- replaced by a revised edition, or
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Section 1
GENERAL

1.1 SCOPE AND OBJECT

It applies to power drive systems (see figure 1) with converter voltages (line-to-line voltage), between 1 kV a.c. and 35 kV a.c., input side 50 Hz or 60 Hz, and load side frequencies up to 600 Hz. Requirements for voltages above 15 kV are not included and are defined by agreement between the manufacturer and the system supplier.

For power drive systems, with voltages above 1 kV, using a step-down input transformer and/or a step-up output transformer in connection with a low voltage converter (below 1 000 V), IEC 61800-2 applies. EMC aspects are covered in IEC 61800-3.

U.S. NOTE: EMC Immunity and Emission requirements of IEC 61800-3 are not applicable within the U.S. Specific safety requirements for drive systems with voltage above 1 kV will be covered in IEC 61800-5.

This standard gives the characteristics of the converters, their topologies and their relationship with the complete a.c. drive system. It also states their performance requirements with respect to ratings, normal operating conditions, overload conditions, surge withstand capabilities, stability, protection, a.c. line earthing, topologies and testing. Furthermore, it deals with application guidelines, such as control strategies, torsion analysis, recommendations for earthing and drive system component integration.

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Section 2
NORMATIVE REFERENCES

NEMA ICS 1-1993	*Industrial Control and Systems General Requirements*
NEMA ICS 1.3-1986 (R1991)	*Preventive Maintenance of Industrial Control and Systems Equipment*
NEMA ICS 7.1-1995	*Safety Standards for Construction and Guide for Selection, Installation, and Operation of Adjustable-Speed Drive Systems*
NEMA ICS 6-1993	*Industrial Control and Systems Enclosures*
NEMA MG 1-1999	*Motors and Generators*
NEMA 250-1997	*Enclosures for Electrical Equipment (1000 volts maximum)*
ANSI/IEEE 519-1992	*IEEE Recommended Practices and Requirements for Harmonic Control in Electric Power Systems*
ANSI/IEEE 597-1983	*Practice and Requirements for General Purpose Thyristor DC Drives*
ANSI/NFPA 70-1999	*National Electrical Code*
UL 508C	*Standard for Power Conversion Equipment*
UL 347	*High Voltage Industrial Control Equipment*
UL 347A	*High Voltage Power Conversion Equipment (draft)*

The following normative documents contain provisions, which, through reference in this text, constitute provisions of this part of IEC 61800. At the time of publication, the editions indicated were valid. All normative documents are subject to revision, and parties to agreements based on this part of IEC 61800 are encouraged to investigate the possibility of applying the most recent editions of the normative documents indicated below. Members of IEC and ISO maintain registers of currently valid International Standards.

(U.S. Difference) Where appropriate, reference in the text of this standard to the following IEC documents is superceded by the preceding references to U.S. documents.

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

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

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

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IEC 60034-2A:1974, *Rotating electrical machines – Part 2: Methods for determining losses and efficiency of rotating electrical machinery form tests (excluding machines for traction vehicles) – First supplement: Measurement of losses by the calorimetric method*

IEC 60034-5, *Rotating electrical machines – Part 5: Degrees of protection provided by the integral design of rotating electrical machines (IP code) – Classification*

IEC 60034-6:1991, *Rotating electrical machines – Part 6: Methods of cooling (IC Code)*

IEC 60034-7, *Rotating electrical machines – Part 7: Classification of types of constructions and mounting arrangements (IM Code)*

IEC 60034-9:1997, *Rotating electrical machines – Part 9: Noise limits*

IEC 60034-14:1996, *Rotating electrical machines – Part 14: Mechanical vibration of certain machines with shaft heights 56 mm and higher – Measurement, evaluation and limits of vibration*

IEC 60034-17:1998, *Rotating electrical machines – Part 17: Cage induction motors when fed from converters – Application guide*

IEC 60034-18-31:1992, *Rotating electrical machines – Part 18: Functional evaluation of insulation systems – Section 31: Test procedures for form-wound windings – Thermal evaluation and classification of insulation systems used in machines up to and including 50 MVA and 15 kV*

Amendment 1 (1996)

IEC 60038:1983, *IEC standard voltages*
Amendment 1 (1994)
Amendment 2 (1997)

IEC 60050-111:1996, *International Electrotechnical Vocabulary (IEV) – Chapter 111: Physics and chemistry*

IEC 60050-151:2001, *International Electrotechnical Vocabulary (IEV) – Part 151: Electrical and magnetic devices*

IEC 60050-351:1998, *International Electrotechnical Vocabulary (IEV) – Part 351: Automatic control*

IEC 60050-441:1984, *International Electrotechnical Vocabulary (IEV) – Switchgear, controlgear and fuses,* Amendment 1 (2000)

IEC 60050-551:1998, *International Electrotechnical Vocabulary (IEV) – Part 551: Power electronics*

IEC 60050-601:1985, *International Electrotechnical Vocabulary (IEV) – Chapter 601: Generation, transmission and distribution of electricity – General*, Amendment 1 (1998)

IEC 60076-1:2000, *Power transformers – Part 1: General*

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IEC 60076-2:1993, *Power transformers – Part 2: Temperature rise*

IEC 60076-3:2000, *Power transformers – Part 3: Insulation levels, dielectric tests and external clearances in air*

IEC 60076-5:2000, *Power transformers – Part 5: Ability to withstand short circuit*

IEC 60076-8:1997, *Power transformers – Part 8: Application guide*

IEC 60146-1-1:1991, *Semiconductor converters – General requirements and line commutated converters – Part 1-1: Specifications of basic requirements*, Amendment 1 (1996)

IEC 60146-1-2:1991, *Semiconductor converters – General requirements and line commutated converters – Part 1-2: Application guide*

IEC 60146-1-3:1991, *Semiconductor converters – General requirements and line commutated converters – Part 1-3: Transformers and reactors*

IEC 60146-2:1999, *Semiconductor converters – Part 2: Self-commutated semi-conductor converters including direct d.c. converters*

IEC 60146-6:1992, *Semiconductor converters – Part 6: Application guide for the protection of semiconductor converters against overcurrent by fuses*

IEC 60204-11:2000, *Safety of machinery – Electrical equipment of machines – Part 11: Requirements for HV equipment for voltages above 1 000 V a.c. or 1 500 V d.c. and not exceeding 36 kV*

IEC 60417 (all parts): *Graphical symbols for use on equipment*

IEC 60529:1989, *Degrees of protection provided by enclosures (IP Code)*, Amendment 1 (1999)

IEC 60664-1:2000, *Insulation coordination for equipment within low-voltage systems – Part 1: Principles, requirements and tests*

IEC 60721-3-1:1997, *Classification of environmental conditions – Part 3: Classification of groups of environmental parameters and their severities – Section 1: Storage*

IEC 60721-3-2:1997, *Classification of environmental conditions – Part 3: Classification of groups of environmental parameters and their severities – Section 2: Transportation*

IEC 60721-3-3:1994, *Classification of environmental conditions – Part 3: Classification of groups of environmental parameters and their severities – Section 3: Stationary use at weather protected locations*, Amendment 1 (1995), Amendment 2 (1996)

IEC 60726:1982, *Dry type power transformers*, Amendment 1 (1986)

IEC 61000-2-4:1994, *Electromagnetic compatibility (EMC) – Part 2: Environment – Section 4: Compatibility levels in industrial plants for low-frequency conducted disturbances*

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IEC 61000-4-7:1991, *Electromagnetic compatibility (EMC) – Part 4: Testing and measurement techniques – Section 7: General guide on harmonics and interharmonics measurements and instrumentation, for power supply systems and equipment connected thereto*

IEC 61136-1:1992, *Semiconductor power converters – Adjustable speed electric drive systems – General requirements – Part 1: Rating specifications, particularly for d.c. motor drives*

IEC 61378-1:1997, *Converter transformers – Part 1: Transformers for industrial applications*

IEC 61800-2:1998, *Adjustable speed electrical power drive systems – Part 2: General requirements – Rating specifications for low voltage adjustable frequency a.c. power drive systems*

IEC 61800-3:1996, *Adjustable speed electrical power drive systems – Part 3: EMC product standard including specific test methods*

ISO 1680:1999, *Acoustics – Test code for the measurement of airborne noise emitted by rotating electrical machines*

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Section 3
DEFINITIONS

For the purposes of this part of IEC 61800, the following definitions, and the definitions given in IEC 60050(111), IEC 60050(151), IEC 60050(351), IEC 60050(441), IEC 60050(551), IEC 60050(601), IEC 60146-1-1, IEC 60146-1-2, and IEC 60146-1-3 apply.

3.1 SYSTEM

3.1.1
a.c. power drive system (PDS)

System with voltage above 1 kV (see figure 1) is an interconnected combination of equipment which provides a means of adjusting the speed of a mechanical load coupled to a motor. consisting of:

– power equipment (possible harmonic filters, input transformer, converter section, possible output transformer, a.c. motor);
– control, protection and auxiliaries;
– motor mounted auxiliary devices: encoders, tachometers, thermal switches and detectors, air blowers, heaters, and vibration sensors.

NOTE 1 Figure 1 illustrates the main functional elements. It also includes equipment which may be optional on many drive systems. It is intended to encompass a wide variety of a.c. drive configuration possibilities. The converter section does not illustrate or imply a specific topology using a specific type of switching device, due to the wide variety of combinations in current use. An input and/or output filter may be included in the converter section (except harmonic filters, which are listed separately). See clause 4 and annex A.

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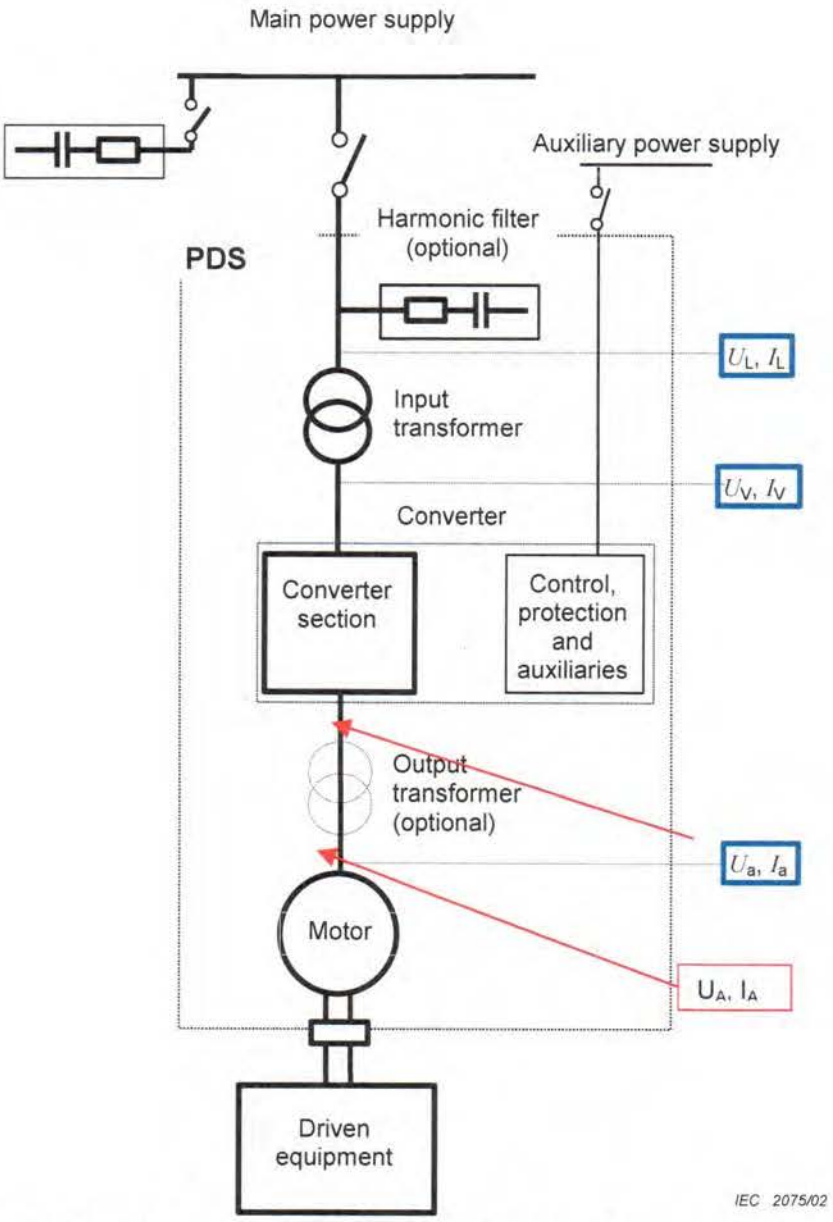


Figure 1 – Functional diagram of an a.c. adjustable speed power drive system (PDS), voltage above 1 kV

NOTE 2 U_a represents the output voltage of the converter and U_A represents the voltage at the terminals of the motor. In the case where there is no output transformer and moderate cable lengths, U_a=U_A.

NOTE 3 Auxiliary supply may also be derived internally from the PDS, if it is considered sufficiently reliable.

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3.1.2
point of coupling

PCC, IPC, PC: these definitions are given in IEC 61000-2-4:

- PCC is the point of common coupling on a public network;
- IPC is the in-plant point of coupling on a private network;
- PC is the point of coupling for either of these cases.

3.1.3
harmonic filter
circuit designed to reduce the flow of harmonic currents into the associated power system

3.1.4
regeneration
process of converting the mechanical energy of the system to electrical energy and transferring it to the input supply.

NOTE During regeneration the motor is working as a generator and the ratings of the motor may be different.

3.1.5
PDS efficiency, η_D
the efficiency, η_D, of the drive system is the ratio of the power delivered by the motor shaft to the total power drawn from the input power supply feeding lines (see figure 1 and figure 25), and is usually expressed as a percentage.

NOTE Auxiliaries and any needed excitation power are included in the power drawn from the input.

3.1.6
power conversion efficiency, η_C
the efficiency, η_C, of the power conversion is the ratio of the power delivered by the converter to the total power drawn from the input power supplies feeding lines, including the converter auxiliaries (see figure 1 and figure 25), and is usually expressed as a percentage.

3.1.7
fundamental frequency
a frequency, in the spectrum obtained from a Fourier transform of a time function, to which all the frequencies of the spectrum are referred. For the purpose of IEC 61800, the fundamental frequency is the same as the power frequency supplying the converter, or supplied by the converter according to the case which is considered [IEV 101-14-50 modified].

NOTE 1 In the case of a periodic function, the fundamental frequency is generally equal to the frequency of the function itself (see IEV 551-20-03 and IEV 551-20-01). The above definition corresponds to the genuine definition of "reference fundamental frequency" according to IEV 551-20-04 and IEV 551-20-02, for which the term "reference" may be omitted where there is no risk of ambiguity. This definition has been adopted for the revision of IEC 61000-2-2 and IEC 61000-2-4.

NOTE 2 In case of any remaining risk of ambiguity, the power supply frequency should be referred to the polarity and speed of rotation of the synchronous generator(s) feeding the system.

NOTE 3 This definition may be applied to any industrial power supply network, without regard to the load it supplies (a single load or a combination of loads, rotating machines or other load), and even if the generator feeding the network is a static converter.

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3.1.8
fundamental component (or fundamental)
the component whose frequency is the fundamental frequency example:

fundamental RMS current: The root mean square function of a periodically varying current waveform that contains no other function than a sinusoidal function. Such a periodically varying current waveform can be represented by the function:

$I(t) = I_p \sin(\omega t + \varphi)$, where I_p is the peak current in amperes, ω is the fundamental angular frequency in radians/second, t is time in seconds, and φ is the phase shift in radians. The fundamental RMS amperes is then defined as:

$$I_{RMS} = \sqrt{\frac{1}{T}\int_0^T I_p^2 \sin^2(\omega t + \varphi)dt}$$

Where $T = 2\pi/\omega$ seconds

3.1.9
harmonic frequency (order *h*)
a frequency which is an integer multiple of the fundamental frequency, the ratio of the harmonic frequency to the fundamental frequency is named harmonic order (recommended notation "*h*") (see IEV 551-20-05, IEV 551-20-07 and IEV 551-20-09).

3.1.10
harmonic component
any of the components having a harmonic frequency, its value is normally expressed as a r.m.s. value.

NOTE For brevity, such a component may be referred to simply as a harmonic.

3.1.11
interharmonic frequency
any frequency which is not an integer multiple of the fundamental frequency (see IEV 551-20-05, IEV 551-20-07 and IEV 551-20-09).

NOTE 1 By extension of the harmonic order, the interharmonic order is the ratio of interharmonic frequency to the fundamental frequency, this ratio is not an integer (recommended notation "*m*").

NOTE 2 In the case where "$m < 1$" the term of sub-harmonic frequency may also be used (see IEV 551-20-10).

3.1.12
interharmonic component
a component having an interharmonic frequency, its value is normally expressed as an r.m.s. value.

NOTE 1 For brevity, such a component may be referred to simply as an interharmonic

NOTE 2 For the purpose of IEC 61800, and as stated in IEC 61000-4-7, the time window has a width of 10 fundamental periods (50 Hz systems) or 12 fundamental periods (60 Hz systems), i.e. approximately 200 ms. The difference in frequency between two consecutive interharmonic components is, therefore, approximately 5 Hz. In case of other fundamental frequencies, the time window should be selected between 6 fundamental periods (approximately 1 000 ms at 6 Hz) and18 fundamental periods (approximately 100 ms at 180 Hz).

3.1.13
harmonic content, *HC*
sum of the harmonic components of a periodic signal [IEV 551-20-12].

NOTE 1 The harmonic content is a time function.

NOTE 2 For practical analysis, an approximation of the periodicity may be necessary.

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NOTE 3 The harmonic content depends on the choice of the fundamental component. If it is not clear from the context which one is used an indication should be given.

NOTE 4 In practice, the sum is limited to the order H.

NOTE 5 The r.m.s. value of the harmonic content is:

$$HC = \sqrt{\sum_{h=2}^{h=H} Q_h^2}$$

where
h is the harmonic order (according to 3.1.9);
Q_h is the r.m.s. value of the harmonic component of order h;
H is 50 for the purposes of this standard.

3.1.14
total harmonic distortion, *THD*
ratio of the r.m.s. value of the harmonic content to the r.m.s. value of the fundamental component or the reference fundamental component of an alternating quantity [IEV 551-20-13].

$$THD = \frac{HC}{Q_1} = \sqrt{\sum_{h=2}^{h=H} \left(\frac{Q_h}{Q_1} \right)^2}$$

where
Q represents either current or voltage
Q_1 is the r.m.s. value of the fundamental component;
h is the harmonic order (according to 3.1.9);
Q_h is the r.m.s. value of the harmonic component of order h;
H is 50 for the purposes of this standard.

3.1.15
total distortion content, *DC*
quantity obtained by subtracting from an alternating quantity its fundamental component or its reference fundamental component.

[IEV 551-20-11]

NOTE 1 The total distortion content includes harmonic components and interharmonic components if any.

NOTE 2 The total distortion content depends on the choice of the fundamental component. If it is not clear from the context which one is subtracted an indication should be given.

NOTE 3 The total distortion content is a time function.

NOTE 4 An alternating quantity is a periodic quantity with zero DC component.

NOTE 5 The r.m.s. value of the total distortion content is

$$DC = \sqrt{Q^2 - Q_1^2}$$

where in addition to notations in 3.1.14:
Q is the total r.m.s. value of the quantity;
see also IEV 101-14-54.

3.1.16
total distortion ratio, *TDR*
ratio of the r.m.s. value of the total distortion content to the r.m.s value of the fundamental component or the reference fundamental component of an alternating quantity.

[IEV 551-20-14]

$$TDR = \frac{DC}{Q_1} = \frac{\sqrt{Q^2 - Q_1^2}}{Q_1}$$

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NOTE 1 The total distortion ratio depends on the choice of the fundamental component. If it is not clear from the context which one is used an indication should be given.

NOTE 2 The total distortion ratio may be approximated to a certain harmonic order. This is to be stated.

NOTE 3 *THD* may be considered as an approximation of *TDR* where interharmonics are disregarded due to their low amplitude.

NOTE 4 The waveform of the voltage on the distribution network is usually less distorted than the waveform of the current. Therefore, the assessment of these two ratios related to voltage, total harmonic distortion *THD* and total distortion ratio *TDR*, leads to the same result. There may be a significant difference when applied to current.

3.1.17
total distortion factor, *TDF*
ratio of the r.m.s. value of the total distortion content to the r.m.s. value of an alternating quantity.

[IEV 551-20-16 and IEV 101-14-55]

$$TDF = \frac{DC}{Q} = \frac{\sqrt{Q^2 - Q_1^2}}{Q}$$

NOTE 1 The total distortion ratio depends on the choice of the fundamental component. If it is not clear from the context which one is used an indication should given.

NOTE 2 The ratio between *TDF* and *TDR* equals the ratio between the r.m.s. value of the fundamental component and the total r.m.s. value. It is the fundamental factor [IEV 551-20-17 and IEV 161-02-22]:

$$FF = \frac{Q_1}{Q} = \frac{TDF}{TDR} \leq 1$$

3.1.18
individual harmonic distortion, *IDR*
ratio of any component to the fundamental.

3.1.19
characteristic current harmonics
orders of the current harmonics produced by converter equipment in the course of normal operation.

NOTE 1 For example, in a six-pulse converter the characteristic current harmonics are the non triple, odd harmonics, $h = 6\,k \pm 1$ (k any integer).

NOTE 2 In addition to power system frequency harmonics, there can be other harmonics resulting from interaction with the converter load. They are called interharmonics.

3.1.20
rated voltage
the r.m.s. line-to-line voltage under rated conditions

Primary side of input transformer: U_{LN}

Converter input: U_{VN}

Converter output: U_{aN}

Motor voltage: U_{AN}

3.1.21
rated fundamental voltage
the r.m.s. value of the fundamental voltage under rated conditions

Primary side of input transformer: U_{LN1}

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Converter input: U_{VN1}

Converter output: U_{aN1}

Motor fundamental voltage: U_{AN1}

3.1.22
rated a.c. current
the r.m.s. value of the a.c. current under rated conditions

Primary side of input transformer: I_{LN}

Converter input: I_{VN}

Converter output: I_{aN}

Rated motor current: I_{AN}

3.1.23
rated fundamental current
the r.m.s. value of the fundamental component of the current under rated conditions

Primary side of input transformer: I_{LN1}

Converter input: I_{VN1}

Converter output: I_{aN1}

Rated fundamental motor current: I_{AN1}

3.1.24
overload capability
maximum current which can be supplied, for a specified period of time, without exceeding established limitations under prescribed operating conditions

Primary side of input transformer: I_{LM}

Converter input: I_{VM}

Converter output: I_{aM}

Motor overload current: I_{AM}

3.2 PDS INPUT PARAMETERS

3.2.1
line-side input power, P_L
the total active power at the line input.

3.2.2
line-side input apparent power, S_L
the total apparent power at the line input.

3.2.3
input total power factor, λ_L
ratio of the total power input, to the apparent power, as determined at the connection of the PDS to the supply.

Example: in a three-phase system where the voltage is considered sinusoidal.

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$$\lambda_L = \frac{U_L \times I_{L1}\sqrt{3} \times \cos\ \varphi_{L1}}{U_L \times I_L \times \sqrt{3}} = \frac{I_{L1}}{I_L} \times \cos\ \varphi_{L1}$$

NOTE 1 The power factor includes the effect of displacement $\cos\varphi_1$ and of harmonics by means of the deformation factor $\nu = \lambda/\cos\varphi$.

NOTE 2 The definition applies to the converter input (subscript V) or to the CDM input line-side (subscript L).

3.2.4
voltage unbalance (imbalance)
in a polyphase system, a condition in which the r.m.s. values of the fundamental component of the line voltages, or the phase angle between consecutive phases, are not all equal.

NOTE 1 The degree of that inequality is usually expressed as the ratios of the negative and zero sequence components to the positive sequence component [IEV 161-08-09, modified].

U_{12}, U_{23} and U_{31} are the three line-to-line voltages, with $\delta_{ij} = (U_{ij}-U_{average})/(3\times U_{average})$ the deviation for each of the three line-to-line voltages, and τ the voltage unbalance as the ratio of the negative sequence voltage amplitude to the positive sequence voltage amplitude,

$$\tau = \sqrt{6 \times \sum_{1}^{3} \delta_{ij}^2}$$

NOTE 2 The above formula in note 1 gives an excellent approximation (with an error of less than 5 % for a band of ±20 % in amplitudes and ±15° in phase shift from the corresponding ideal line to neutral balance system – positive sequence or negative sequence). The much more simple approximation:

$\tau = (2/3) \times [\ (U_{max} - U_{min})/U_{average}\ ]$

provides acceptable results for τ up to 7 % (absolute error less than 1 %). Another simple approximation gives results with a comparable error:

$\tau = \text{MAX}\ [(U_{ij} - U_{average})/U_{average}\ ]$.

NOTE 3: NEMA voltage unbalance (based on amplitude computation) gives a higher number than IEC voltage unbalance (based on fazorial computation), and τ the IEC simple approximation as above. See below:

NEMA voltage unbalance is defined as:
Voltage Unbalance = [(V_{max} - V_{min}) / V_{avg}] x 100
where:
V_{max} = Maximum line-to-line voltage
V_{min} = Minimum line-to-line voltage
V_{avg} = Average of the three line-to-line voltages

3.2.5
supply transient overvoltage
peak instantaneous voltage that may appear between the input lines to the PDS, with the PDS disconnected.

3.2.6
supply transient energy
the energy which the supply system, due to a transient, is capable of delivering at the PDS terminals.

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3.3 CONVERTER

3.3.1
converter section (voltage above 1 kV)
electronic power converter employing semiconductors for the transformation of electric power to be supplied to a motor operating at voltage above 1 kV and not exceeding 35 kV according to figure 1. Examples:

rectifier: A converter that changes AC power to DC power.

inverter: A converter that changes DC power to AC power.

pulse-width modulated inverter (PWM): An inverter whose switching will vary the time duration of voltage or current for control of the output.

converter: A combination of the converter section, control protection and auxiliary circuit included on one chassis. The converter may include a disconnecting means. (See Figure 1-2-1.Converter)

3.3.2
converter input filter
circuits connected to the power input of the converter to reduce dv/dt (voltage stress of transformer insulation) or radio frequency emissions.

3.3.3
converter d.c. link voltage, U_d
average value of the voltage in the d.c. link (on the input converter side).

3.3.4
converter d.c. link current, I_d
average value of the current in the d.c. link (on the input converter side).

3.3.5
snubber (circuit)
a sub-circuit connected to one or more power semiconductor devices in order to relieve it (them) of stress in regard of high rate of rise of current or voltage, overvoltage transients, switching losses, etc.

3.3.6
d.c. link
power d.c. circuit linking the input converter and the output converter of an indirect converter, consisting of capacitors and/or reactors to reduce d.c. voltage or d.c. current ripple.

3.3.7
converter output filter
circuits connected to the power output of the converter to reduce dv/dt (voltage stress of motor insulation and generating bearing currents) or harmonics (losses).

3.3.8
a.c. converter output power, P_{a1}
the fundamental power at the converter output terminals.

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3.3.9
apparent converter output power, S_a
the total apparent power at the converter output terminals.

3.3.10
dynamic short-circuit output current
the transient d.c. or a.c. current which flows from the converter into a short-circuit across the output terminals.

3.3.11
operating frequency range
range of fundamental frequencies over which the converter output is controlled (f_{min}, f_{max}), under specified load conditions.

3.4 PDS OUTPUT PARAMETERS

3.4.1
load envelope
area in torque versus speed in which the PDS is intended to operate under continuous load conditions.

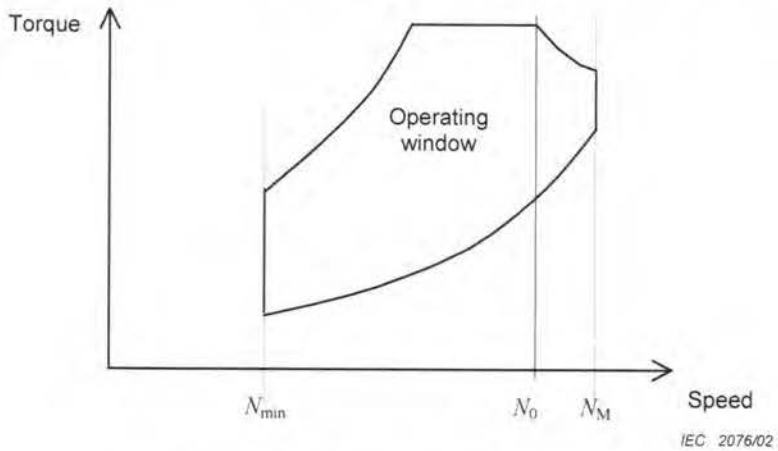


Figure 2 – Example of load envelope

3.4.2
minimum operating speed, N_{min}
minimum motor operating speed required by driven equipment.

3.4.3
maximum operating speed, N_{max}
maximum motor operating speed required by driven equipment.

3.4.4
base speed, N_0
highest motor speed at which the PDS is capable to deliver continuously the rated torque.

NOTE Base speed is the transition point between constant torque and field weakening operation.

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3.4.5
field weakening operation
operation with reduced flux in a speed range between base speed (N_0) and maximum speed (N_{max}).

3.4.6
air-gap torque pulsation
cyclic fluctuation of motor air-gap torque at under steady-state conditions, defined as M_d peak-to-peak value.

3.4.7 *(U.S. difference)*
motor current
The rms magnitude of the fundamental current at the terminals of the motor.

3.4.8
motor voltage
The rms value of the fundamental sinusoidal voltage at the terminals of the motor.

3.5 CONTROL

3.5.1
control system
electronic system which provides actuation of the power converter and status information as a result of various commands and feedbacks. See Figure 1, Control Protection and Auxiliary.

3.5.2
controlled variable
system variable, in open-loop or closed-loop control of PDS.

NOTE Some examples of controlled variables are voltage, stator current, frequency, speed, slip and torque.

3.5.3
service variable
specified variable, usually related to ambient conditions (e.g. temperature), for which the feedback control system is to correct in attempting to maintain the ideal value of the controlled variable.

3.5.4
operating variable
specified variable (e.g. load torque for a speed controlled drive), other than those arising from service conditions, for which the feedback control system is to correct in attempting to maintain the ideal value of the controlled variable.

3.5.5
open-loop control
control which does not use the measurement of the controlled variable.

3.5.6
feedback control/closed-loop control
control in which the control action is dependent on the measurement of the controlled variable.

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3.5.7
stimulus
any excitation of a system which causes a reaction in response.

NOTE Examples are given in 7.2.2.

3.5.8
disturbance
undesired and most frequently unpredictable change in an input variable, other than the reference variable

3.5.9
time response
the variation in time of an output variable of a system, produced by a specified variation of one of the input variables

3.5.10
step response
the time response of a system produced by a step-wise variation of one of the input variables

NOTE When the variation of the input variable is equal to one unit, the step response is called the unit step response.

3.6 TESTS

3.6.1
type test
test of one or more devices made to a certain design to show that the design meets certain specifications.

[IEV 151-16-16 modified]

3.6.2
routine test
test to which each individual device is subjected during or after manufacture to ascertain whether it complies with certain criteria.

[IEV 151-16-17 modified]

3.6.3
sampling test
test on a number of devices taken at random from a batch.

[IEV 151-16-20 modified]

3.6.4
special test
test additional to type and routine tests, made either at the discretion of the system supplier or according to an agreement between the system supplier and customer or his representative.

[IEC 61800-2, 7.1.4 modified]

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3.6.5
acceptance test
contractual test to prove to the customer that the device meets certain conditions of its specification.

[IEV 151-16-23]

3.6.6
commissioning test
test on a device or equipment carried out on site, to prove the correctness of installation and operation.

[IEV 151-16-24, modified]

3.6.7
witness test
any of the above tests performed in the presence of the customer, the user or his representative. (IEC 61800-2, 7.1.8)

3.6.8
separate component test
test on each individual main component which constitutes a PDS (transformer, motor, etc.).

3.6.9
drive system test
test on total PDS to ascertain total performance of the system.

3.7 SYMBOLS

Table 1 summarizes symbols which are the most commonly used.

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Table 1 – Symbols

Symbol	Unit	Definition	Parameter
I_{aM}	A	3.1.24	Converter Overload current (overload capability)
I_{aN}	A	3.1.22	Converter Rrated continuous output current
I_{aN1}	A	3.1.21	Converter Rrated fundamental output current
I_d	A	3.3.4	d.c. link current
I_{LN}	A	3.1.22	Line-side a.c. rated current of the PDS
I_{LN1}	A	3.1.23	Line-side fundamental a.c. rated current of the PDS
I_{VN}	A	3.1.22	Rated input current of the PDS
J	kgm² or Nms²		Moment of inertia
M_d	Nm		Air gap torque (electromagnetic torque)
M_s	Nm		Shaft torque
N	r/min		Motor speed
N_0	r/min	3.4.4	Base speed
N_M	r/min	3.4.3	Maximum operating speed
N_{min}	r/min	3.4.2	Minimum operating speed
P_{aN1}	W		Rated converter a.c. output power
P_{LN}	W	3.2.1	Rated input power
P_S	W		Output power (on the shaft of the motor)
R_{SI}		IEC 61800-3 B.2.1.3.6	Short-circuit current ratio R_{SI}=(S_{SC} at a given point)/S_N equipment
S_{aN}	VA		Rated converter apparent output power
S_{LN}	VA	3.2.2	Rated input apparent power
TDR_a	%	See 3.1.16	Converter output total distortion ratio
TDR_L	%	See 3.1.16	Line-side total distortion ratio (with interharmonics)
THD_a	%	See 3.1.14	Converter output total harmonic distortion
THD_L	%	See 3.1.14	Line-side total harmonic distortion (without interharmonics)
U_{aN}/f_{aN}	V/Hz		Rated voltage to rated frequency ratio
U_{aN1}	V	3.1.21	Load side fundamental a.c. rated voltage
U_{LN}	V	3.1.20	Rated system voltage
U_{VN}	V	3.1.20	Converter input rated a.c. voltage
U_{VN1}	V	3.1.21	Converter input rated a.c. fundamental voltage
cos φ_{L1}		IEC 61800-2	Line-side displacement factor
cos φ_{V1}		IEC 61800-2	Converter input displacement factor
f_{LN}	Hz		Rated line frequency
η_C	%	3.1.6	Efficiency of power conversion
η_D	%	3.1.5	Efficiency of PDS
η_M	%	11.1	Efficiency of the motor
η_T	%	11.1	Efficiency of the transformer
λ_L		3.2.3	Input total power factor

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NOTE 1 The index "L" is used for the line side (primary side of transformer) parameters or variables.

NOTE 2 The index "V" is used for the converter input side parameters or variables.

NOTE 3 The index "d" is used for the d.c. link parameters or variables.

NOTE 4 The index "a" is used for the converter output side parameters or variables.

NOTE 5 The index "A" is used for the motor side parameters or variables.

NOTE 6 The second index "N" is used for rated condition.

NOTE 7 The third index "1" is used for the fundamental component of a variable (order 1), etc.

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Section 4
OVERVIEW OF DRIVE SYSTEM TOPOLOGIES

4.1 TOPOLOGIES CLASSIFICATION

The various drive systems topologies may be classified according to the following main criteria:

- converter configuration;
- commutation mode;
- motor type.

Any combination of the situations below can be used to form a drive system topology. Examples of commonly used drive system topologies are shown in annex A.

The classification of converters is between drive systems with *indirect converters* or *direct converters*. The second criterion for classification is with the commutation mode which may be external commutation or self-commutation.

4.2 CONVERTER CONFIGURATION

4.2.1 Indirect converter

The power conversion from a fixed frequency and voltage a.c input to a variable frequency and voltage a.c. output is performed with an intermediate d.c. link, as in figure 3.

The d.c. link includes one or more filtering devices (series reactor, parallel capacitor or both).

In the case of an inductive d.c. link, the motor-side converter is named current source inverter (CSI). In the case of a capacitive d.c. link it is named voltage source inverter (VSI).

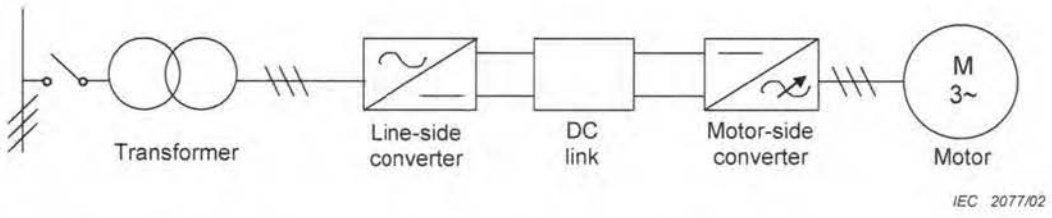


Figure 3 – General structure of a drive system with an indirect converter

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4.2.2 Direct converter

The power conversion from a fixed frequency and voltage a.c input to a variable frequency and voltage a.c. output is performed without an intermediate d.c. link, as in figure 4.

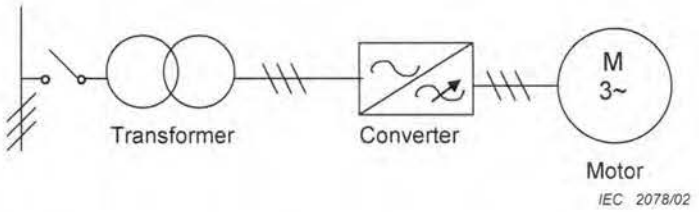


Figure 4 – General structure of a drive system with direct converter

The transformer in both figures usually presents one line-side three-phase winding and one or more secondary three-phase windings, depending on the nature of the connected converter. The latter may consist of multiple six-pulse converter modules, connected in series and/or parallel and sometimes with a sequential control, with the scope to improve the harmonic content and the power factor respectively.

4.2.3 Commutation mode

4.2.3.1 External commutation

External commutation means that commutation is due to a source outside the converter. This kind of commutation includes line commutation and load commutation. In case of indirect converters with a load commutated motor-side converter, this is named load commutated inverter (LCI).

4.2.3.2 Self-commutation

Self-commutation means that commutation is performed by means of components within the converter.

4.3 MOTOR TYPE

The main motor types include polyphase *synchronous motors* and *induction motors*. The most common configurations of both types are three-phase or multiple three-phase stator winding systems. Induction motors may be subdivided into cage induction motors and wound rotor induction motors.

Figure 5 shows an example of a configuration with multiple line-side and motor-side converter modules and with a motor with two separate stator winding systems.

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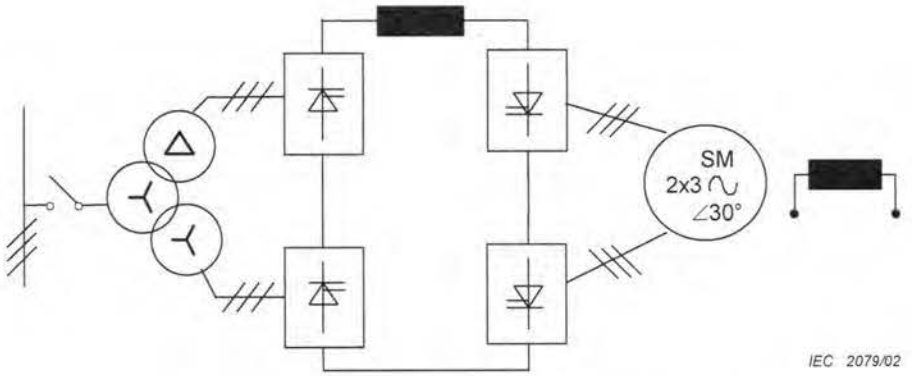


Figure 5 – Example of multiple converter modules and separate stator winding systems motor

4.4 BY-PASS AND REDUNDANT CONFIGURATIONS

REDUNDANCIES *(U.S. Difference)*

The adjustable-speed drives are often applied to critical systems which require high availability. Availability can be enhanced by designing the adjustable-speed drive system with redundancies, which can be provided at the component level, subassembly level, and at the system level.

Drive systems may have by-pass and/or redundant configurations to satisfy different aims, among which are the following:

- normal changing from a variable frequency supply to a mains frequency supply at the end of the system starting procedure;
- emergency switching from a variable frequency supply to a mains frequency supply, in case of power converter failures, in such a way as to allow operation of the system at a fixed speed;
- maximum system availability and reliability, obtainable by including multiple power converter channels, acting as selectively separable subsystems – each of them allowing the operation of the system in case of partial failure, sometimes at reduced power, each drive subsystem acting therefore as an adjustable frequency bypass channel.

NOTE In the case of bypass topology, care should be taken regarding the motor rating for the starting conditions without the converter.

Figure 6 shows an example of a bypass configuration for a drive system with indirect conversion: the bypass channel may include a transformer for voltage level matching.

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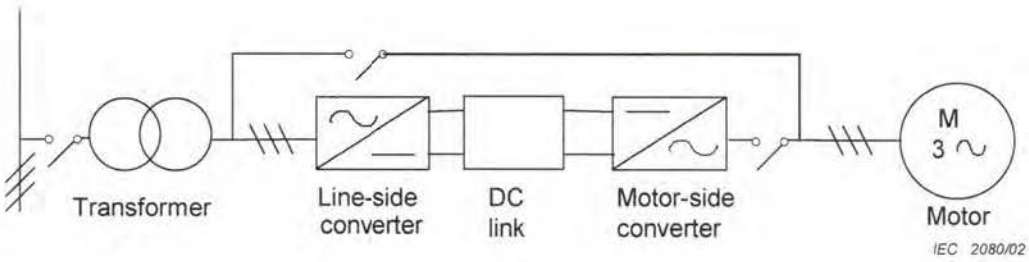


Figure 6 – Bypass configuration for system with indirect converter

An example of a redundant configuration is given in figure 7.

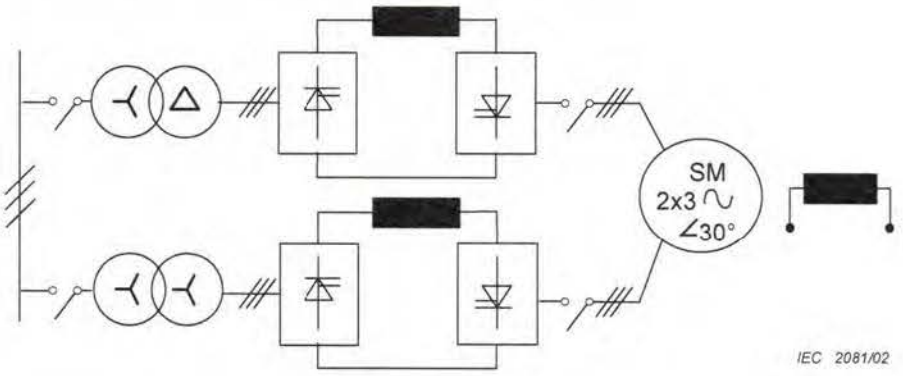


Figure 7 – LCI-synchronous motor in a partly redundant configuration

4.5 REGENERATIVE AND DYNAMIC BRAKING

4.5.1 Regenerative braking

Torque and speed can, in general, have two polarities, so that there are four quadrants of operation. If torque and speed have the same polarity, then power is flowing from the line to the motor. On the other hand, if the torque opposes the direction of rotation, then power is flowing from the motor to the line.

CONSIDERATIONS FOR DRIVES WITH REGENERATIVE CAPABILITY *(U.S. Difference)*

Some adjustable-speed drives covered by this publication have the capability of operating continuously in the regenerative mode in which the motor is converting mechanical energy from the load into electrical energy, which the drive then returns to the AC input supply. The user should be aware of this possibility in the application, and the ramifications with respect to the inverter, motor and input supply.When power flows from the line to the motor it is called "motoring operation," when power flows from the motor to the line it is called "regenerating operation."

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Many of the topologies illustrated in annex A are capable of four quadrant operation and therefore, regenerative braking.

4.5.2 Dynamic braking

In case of dynamic braking, energy is dissipated in a resistor.

As an example, figure 8 shows a VSI-inverter drive with a resistor in parallel to the d.c. link capacitor; when current reversal occurs, the chopper operates in such a way as to control the capacitor voltage, allowing the braking energy to be dissipated in the resistor.

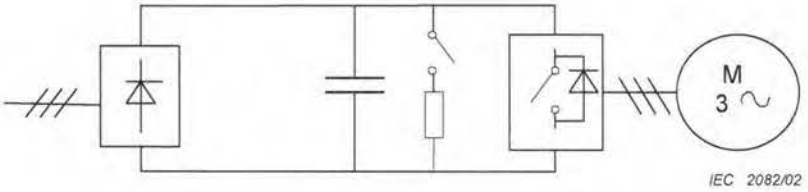


Figure 8 – Example of dynamic braking

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Section 5
SERVICE CONDITIONS

5.1 INSTALLATION AND OPERATION

5.1.1 Electrical service conditions

5.1.1.1 Normal service conditions

Unless otherwise specified, the PDS shall be designed to operate under the electrical service conditions specified in table 2 below. The corresponding EMC acceptance criteria in the same structure can be found in 5.2 of IEC 61800-3 Table 2 – Service conditions for the voltage supply at the PDS terminals (main and auxiliary).

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Phenomenon	Level	Reference document
Frequency variations	f_{LN} ± 2 % f_{LN} ± 4 % (for separated supply networks) **SEE TABLE 2-1 FOR SERVICE CATEGORY**	IEC 61800-3
Frequency rate of change	≤2 % f_{LN}/s **SEE TABLE 2-1 FOR SERVICE CATEGORY**	IEC 61800-3
Voltage variations	±10 % +10 %, –15 % ≤ 1 min (see note 1) **SEE TABLE 2-2 FOR SERVICE CATEGORY**	IEC 61800-3
Voltage fluctuations	maximum step amplitude: – 12 % within the tolerance band – minimum interval between steps: 2 s – rise time: ≥5 periods of the supply **SEE TABLE 2-2 FOR SERVICE CATEGORY**	IEC 61800-3
Voltage dips	10 – 50 % t ≤ 100 ms 10 – 100 % t ≤ 5 s (see note 2)	IEC 61800-3
Voltage unbalance	main supply: 2 % (zero sequence and negative sequence components) auxiliary supply: 3 % (zero sequence and negative sequence components) **SEE TABLE 2-3 FOR SERVICE CATEGORY**	IEC 61800-3
Voltage harmonics: steady state transient	 THD ≤ 10 % steady state THD ≤ 15 % t ≤ 15 s (see note 3)	IEC 61800-3
Voltage interharmonics: steady state transient	 IDR ≤ 0,5 % IDR ≤ 0,75 % t ≤ 15 s	IEC 61000-2-4 Annex A
Commutation notches	depth: 40 % U_{LWM} main supply, area: 125 % × degrees auxiliary supply, area: 250 % × degrees	IEC 61800-3

NOTE 1 Rated operation at voltages below 100 % of rated voltage shall be subject to agreement between the customer and the system supplier.

NOTE 2 In reference to performance criteria, as defined in table 1 of IEC 61800-3, for the main power port, the smaller dips of this table are associated with performance criterion B or C and the largest with criterion C. For the auxiliary power ports, the smaller dips are associated with performance criterion A or B and the largest with criterion B.

NOTE 3 These figures represent the service conditions when the PDS is in operation.

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Table 2-1 *(U.S. Difference)*
SERVICE CATEGORIES BY AC INPUT FREQUENCY VARIATIONS

Variation	Service Category				Possible Consequence if exceeded
	I	II	III	IV	
Range	±1%	±2%	±2%	±5%	DP
Rate of Change	±1%/sec	±1 %/sec	±2%/sec	±5%/sec	DP

DP - Drive is functional with degraded performance

A decrease in frequency is assumed not to coincide with an increase in line voltage and vice versa.

Table 2-2 *(U.S. Difference)*
SERVICE CATEGORIES BY AC VOLTAGE AT INPUT TO CONVERTER

Variation	Service Category				Possible Consequence if exceeded
	I	II	III	IV	
a. Steady state (%)	+10/-5	±10	±10	±10	DP
b. Short Time (0.5 to 30 cycles)					
Rectifier operation only, up to rated current (%)	+15/-10	+15/-10	±15	N/A	T
Inverter operation up to rated current (%)	+15/-7.5	+15/-10	±15	N/A	T
c. Short Time 05 to 30 cycles				+10/-20	T

DP - Drive is functional with degraded performance

T- Interruption of service by protective devices.

Table 2-3 *(U.S. Difference)*
SERVICE CATEGORIES BY AC INPUT VOLTAGE UNBALANCE*

Variation	Service Category				Possible Consequence if exceeded
	I	II	III	IV	
a. Steady state (%)	1%	2%	2%	2%	DP/T

*Voltage Unbalance = $[(V_{max} - V_{min})/V_{avg}] \times 100$

Where V_{max} = Maximum line to line voltage

V_{min} = Minimum line to line voltage

V_{avg} = Average of the three line to line voltages

DP - Drive is functional with degraded performance

T- Interruption of service by protective devices.

Certain applications may require variation levels beyond Service Category IV. An agreement between the manufacturer and customer is required.

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5.1.1.2 Source impedance

Protective devices of the PDS, particularly the line feeder protection (see 9.3), shall be designed to operate properly within a range of specified short-circuit current ratios (R_{SI}).

The minimum R_{SI} ratio for a standard design PDS to meet rated performance shall be 20, determined at the point of coupling (PC).

The maximum R_{SI} ratio for a standard design PDS to meet protection conditions shall be 100, determined at the point of coupling (PC).

In the case of a custom design, the actual range of R_{SI} shall be specified if less than 20 or higher than 100.

5.1.1.3 Repetitive and non-repetitive transients

A typical a.c. voltage waveform contains repetitive and non-repetitive transients. The transients are caused by converter commutation, switching of switchgears on the network, and disturbances on the power system.

The PDS shall be designed to operate in an environment with non-repetitive transients caused by switching the transformer of the PDS (see 9.2.1) or other transformer supplying the point of coupling (PC).

NOTE If unusually high overvoltages may occur at the PC, this should be specified by the customer. For example, a customer specification for a 6 kV supply states:

- in the case of remote switching: 15 kV voltage surge, 250/2 500 μs;
- in the case of nearby switching: 12,3 kV voltage surge, 50/400 μs.

5.1.1.4 Unusual electrical service conditions

The unusual service conditions shall be subject to a special agreement between the customer and the system supplier.

5.1.2 Environmental service conditions

5.1.2.1 Climatic conditions

The PDS (with the possible exceptions of the power transformer and motor when installed at different locations) shall operate under the environmental conditions specified in IEC 60721-3-3 for class 3K3, and section 2 of IEC 60146-1-1 for the cooling medium. This includes the following:

a) temperature range of the cooling medium

air	0 °C to +40 °C
inlet water	+5 °C to +30 °C

b) ambient temperature range

+5 °C to +40 °C

+30 °C	daily average, air
+25 °C	yearly average, air;

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c) relative humidity

5 % to 85 % without condensation;

d) altitude

1 000 m maximum above sea level;

e) dust and solid particle content

equipment of standard design is designed for clean air, pollution degree 2, any other condition constitutes "unusual service conditions" and requires specification by the customer (see IEC 60529 for degrees of protection for enclosures);

f) extended shut down periods

the customer should indicate, if such periods are foreseen, even if the ambient conditions are in the range defined above.

5.2.1.2 Mechanical installation conditions

The PDS, (with the possible exceptions of the power transformer and motor, when installed at different locations) shall be installed indoors on a rigid mounting surface or in a supplementary enclosure, which do not seriously interfere with the ventilation or cooling system. An air-conditioner may be furnished to enhance the reliability.

Other installation circumstances require special consideration and require specification and consultation with the converter manufacturer.

Vibration shall remain within the limits of IEC 60721-3-3, class 3M1, which is considered normal for stationary equipment. Vibration beyond these limits or use on non-stationary equipment are considered unusual mechanical conditions.

Table 3 – Installation vibration limits

Frequency Hz	Amplitude mm	Acceleration m/s^2
$2 \leq f < 9$	0,3	not applicable
$9 \leq f < 200$	not applicable	1

The main transformer (if any) and the motor shall comply with their applicable product standards (IEC 60076 or IEC 60726 and IEC 60034, respectively).

5.1.2.3 Unusual environmental service conditions

The use of power converter equipment, associated drive control, and drive equipment under conditions different from the usual conditions listed in IEC 60146-1-1 shall be considered unusual. The customer shall specify these unusual service conditions.

Operating conditions not specified as usual environmental conditions in 5.1.2 should be coordinated between the customer and the supplier of the equipment.

Identified unusual service conditions for the converter are the following:

a) exposure to damaging fumes;

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b) exposure to excessive moisture (relative humidity greater than 85%) and relative humidity changes (exceeding 0,005 p.u./h);

c) exposure to excessive dust;

d) exposure to abrasive dust;

e) exposure to steam or water condensation;

f) exposure to steam or oil vapor;

g) exposure to explosive mixtures of dust or gases;

h) exposure to salt air;

i) exposure to abnormal vibration, shock or tilting;

j) exposure to weather or dripping water;

k) exposure to unusual transportation or storage conditions;

l) exposure to extreme or sudden changes in temperature (exceeding 5 K/h);

m) cooling water containing acid or impurities which cause excessive scale, sludge, electrolysis or corrosion or obstruction, sea and hard water;

n) unusually high nuclear radiation;

o) altitude above 1 000 m;

p) outdoor equipment.

For unusual service conditions of the main transformer (if any) and motor, refer to the applicable product standards (IEC 60076 or IEC 60726 and IEC 60034, respectively).

5.1.3 Commissioning

Unless otherwise agreed upon, commissioning has the same normal and unusual service conditions as operation.

5.2 TRANSPORTATION

5.2.1 Climatic conditions

5.2.1.1 General

Equipment shall be capable of transportation in the supplier's package, under environmental conditions, as specified in class 2K3 of IEC 60721-3-2.

5.2.1.2 Ambient temperature

–25°C to +55°C

–25°C to +70°C up to 24 hr.

NOTE 1 Temperature limits refer to the ambient temperature immediately surrounding the equipment (for example, inside a container).

NOTE 2 These limits apply with cooling liquid removed.

NOTE 3 Lower limits for the highest temperature are possible, provided a warning is given.

5.2.1.3 Relative humidity

Less than 95% at +40°C

NOTE Some combinations of temperature and humidity may cause condensation.

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5.2.1.4 Atmospheric pressure

Range 86 kPa to 106 kPa

The main transformer (if any) and the motor shall comply with their applicable product standards. (IEC 60076 or IEC 60726 and IEC 60034, respectively.)

5.2.1.5 Unusual climatic conditions

Temperatures below –25°C.

Where transportation temperatures below –25°C are anticipated, the use of heated transport or the removal of selected low temperature sensitive components is required.

5.2.2 Mechanical conditions

5.2.2.1 General

Equipment shall be capable of transportation, in the supplier's package, within the limits prescribed in class 2M1 of IEC 60721-3-2. This includes the following requirements as far as vibration and shock are concerned.

5.2.2.2 Vibration limits

Limits are given in table 4.

Table 4 – Transportation vibration limits (see class 2M1 IEC 60721-3-2)

Frequency Hz	Amplitude mm	Acceleration m/s^2
$2 \leq f < 9$	3,5	Not applicable
$9 \leq f < 200$	Not applicable	10
$200 \leq f < 500$	Not applicable	15

5.2.2.3 Shock limits

The limits are those corresponding to a free fall height of 0,1 m.

NOTE 1 If a shock and vibration environment beyond those limits is anticipated, special packaging or transport are required.

NOTE 2 If a less damaging environment is known to exist, packaging may reflect reduced requirements by agreement between component manufacturers/system supplier, customer and carrier.

NOTE 3 The main transformer (if any) and the motor shall comply with their applicable product standards. (IEC 60076 or IEC 60726 and IEC 60034, respectively).

5.3 STORAGE OF EQUIPMENT

5.3.1 General

The equipment shall be placed under adequate cover immediately upon receipt if packing coverings are not suitable for outdoor or unprotected storage.

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5.3.2 Climatic conditions

Equipment shall be capable of storage under environmental conditions as specified in IEC 60721-3-1. This includes the following requirements.

a) Ambient temperature class 1K4:

   –25 °C to +55 °C

b) Relative humidity class 1K3:

   5 % to 95 %

c) Atmospheric pressure:

   86 kPa to 106 kPa

These limits apply with cooling liquid removed.

Storage conditions and duration shall be defined and agreed upon between customer and system supplier.

For the converter, the transformer and the motor, the applicable product standards (IEC 60146, IEC 60076 or IEC 60726 and IEC 60034, respectively) take precedence.

5.3.3 Specific storage hazards

The following require particular attention:

a) **water** – except for equipment specifically designed for outdoor installation: equipment shall be protected from rain, snow, sleet, etc.;

b) **condensation** – sudden changes in temperature and humidity should be avoided;

c) **corrosive materials** – equipment shall be protected from salt spray, hazardous gases, corrosive liquids, etc.;

d) **time** – the above specifications apply to shipping and storage with a total duration of up to six months; longer storage times may require special consideration (i.e. reduced ambient temperature range such as in class 1K3 of IEC 60721-3-1);

e) **rodents and fungi** – when storage conditions are likely to involve rodent or fungus attack, equipment specifications shall include protective items:

   rodents – materials on the outside of the equipment and the size of apertures for cooling, connection, etc. shall be specified such as to discourage rodent attack or entry;

   fungi – materials shall be specified for a degree of fungus resistance suitable for the storage and operating environments.

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Section 6
RATINGS

6.1 POWER DRIVE SYSTEM (PDS)

6.1.1 General

The main power components specifications of the PDS are within the responsibility of the system supplier (see clause 8).

6.1.2 PDS input ratings

6.1.2.1 Input voltages and frequencies

The PDS input voltage and frequency rating shall be stated by the customer.

Standard values are as follows according to IEC 60038: 2,4 kV, 3 kV, 3,3 kV, 4,16 kV, 6 kV, 6,6 kV, 10 kV, 11 kV, 12,47 kV, 13,2 kV, 13,8 kV, (15 kV), 20 kV, 22 kV, 24,94 kV, 33 kV, 34,5 kV. Different, non-standard voltage values may be specified for system optimization or special circumstances.

6.1.2.2 Input currents

There are several input currents that shall be provided by the system supplier at rated line voltage and rated PDS load:

- the total r.m.s. current of the PDS – I_{LN}, it may include the current I_{XLN} required by auxiliaries if supplied on the same line, at the same voltage level as the PDS;
- the harmonic current spectrum of the PDS including the fundamental – I_{LNh}, h is up to 50;
- the currents required by auxiliaries including harmonics, if relevant, for each source – I_{XNj}.

These values shall be stated by the system supplier at the minimum specified a.c. line impedance (including the converter supply transformer), and with no background supply-voltage distortion.

6.1.3 PDS output ratings

6.1.3.1 Operating speed range

The operating speed range shall be defined using the following parameters:

- N_{min} = minimum operating speed
- N_o = base speed
- N_{max} = maximum operating speed.

Coordination is required between the system supplier and the driven equipment supplier regarding critical speeds (see 9.4.1).

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6.1.3.2 Torque and power rating

Continuous output rating and possible overload capability of the PDS should be specified in terms of continuous and overload torque or power available at motor shaft at speeds defined above.

Coordination is required between the system supplier and the driven equipment supplier regarding torque pulsations (see 9.4).

6.1.3.3 Operating quadrants

The above ratings shall be given for all operating quadrants as agreed between system supplier and customer.

6.1.4 PDS efficiency and losses

The PDS subsystems included in the determination of the overall efficiency shall be stated. See clause 11 for the determination procedure.

NOTE All auxiliary losses (example: cooling system, excitation, control) are included in the PDS losses, as those of a self-ventilated motor.

The losses or efficiency of the PDS shall be specified by the system supplier at rated load and base speed. If guarantees are given, they shall always refer to rated values and rated conditions. In such a case, the following tolerances on power losses shall apply:

- total system 0%+7%
- converter 0% +10%
- transformer and motor 0% +10% according to their product standard
- other components according to their product standard if any,
  or 0% +10% in other cases.

An example of variation of efficiency and losses versus speed is given in figure 9.

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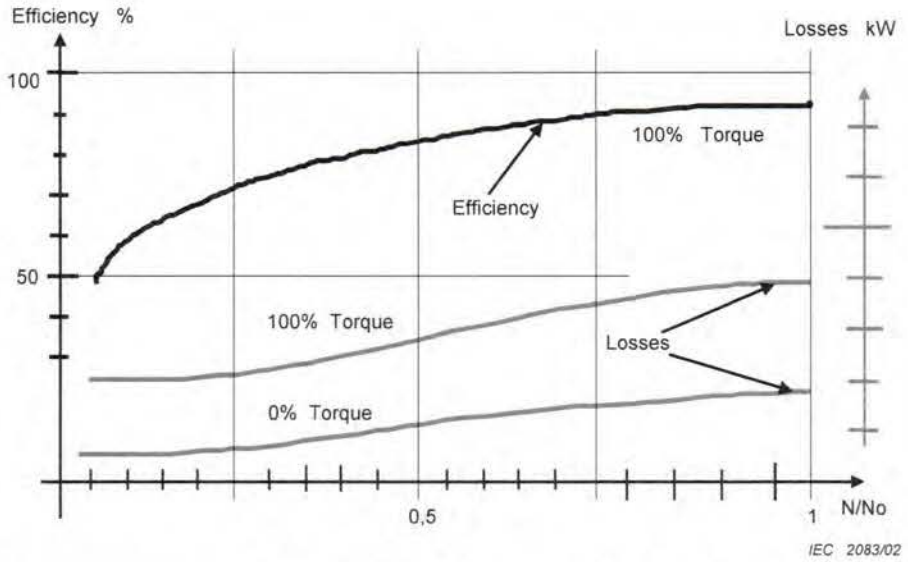


Figure 9 – Typical curves for efficiency and losses of a PDS at constant flux operation

6.1.5 PDS overload capability

Besides the rated value under continuous load conditions (see 6.1.2.2), the system supplier may assign additional values of the rated current, each under specified overload conditions, i.e. a converter equipment may be assigned by the system supplier different ratings for different types of load. The overload capability applies to the rated speed range.

The overload capability of the PDS can be specified as an intermittent load duty, or as repetitive load duty. A wider classification, as well as calculation methods can be found in IEC 61136-1. Special overload conditions should be agreed between the customer and the system supplier/component manufacturers.

For example, typical overload magnitudes and duration are given in table 3 of IEC 60146-1-1.

For any type of duty cycle, the r.m.s. value of the current over the complete cycle shall not exceed the rated current. Table 5 and figure 10 show three usual examples of a 1 min overload with a 10 min load cycle.

Table 5 – Example of reduced maximum continuous load as a function of an overload

Overload		Reduced continuous load	
Amplitude I_{aM} p.u. of rated	Duration t_{aM} min	Maximum amplitude of I_{aR} p.u. of rated I_{aN}	Duration (t_s-t_{aM}) min
1,5	1	0,928 1	9
1,25	1	0,968 1	9
1,1	1	0,988 1	9

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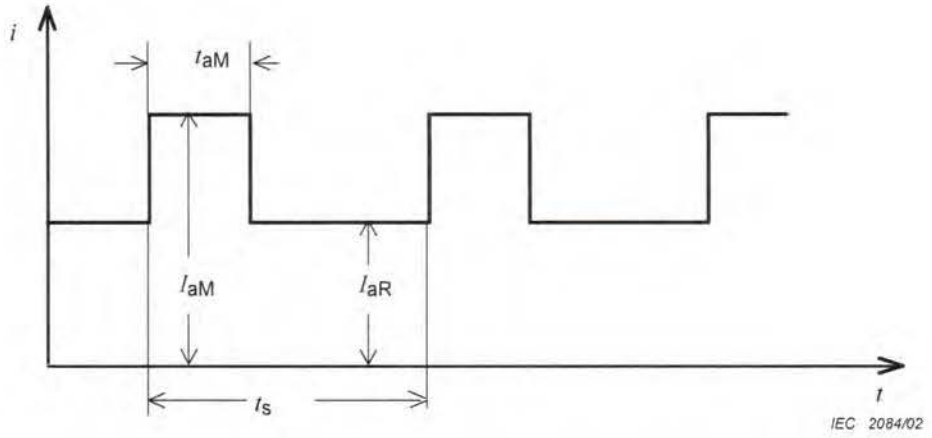


Figure 10 – Overload cycle example

For repetitive load duty, the rated fundamental converter current shall correspond, as a minimum, to the r.m.s. value of the motor current for a full period of the motor duty cycle and the overload capability of the converter shall be adequate for the load duty cycle.

For continuous duty, the rated fundamental converter current I_{aN1} shall correspond, as a minimum, to the continuous motor current necessary to supply the specified continuous motor torque. In the case of intermittent load duty, the overloads shall not cause the converter current to exceed its overload rating.

6.2 CONVERTER

6.2.1 Converter input ratings

The converter manufacturer shall state the input voltage and frequency rating of the converter assembly. Standard values of the line frequency are 50 Hz or 60 Hz.

The input rated current shall be stated at rated line voltage and rated PDS load:

- the rated r.m.s. current of the converter input – I_{VN}
- the harmonic current spectrum of the converter input including the fundamental – I_{VNh}, h is up to 40 or 50.

These values shall be stated at the minimum specified a.c. line impedance (including transformer).

6.2.2 Converter output ratings

In the case where the PDS includes an input transformer, the manufacturer of the PDS shall specify the earthing status of the neutral (on the converter side of the transformer) (see 9.3).

The operating frequency and voltage range at the specified or typical output impedance (including motor and transformer if any) shall use the following parameters:

- U_{aN1} = rated fundamental output voltage

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- f_{min} = minimum operating frequency
- f_M = maximum operating frequency.

The rated output current shall be stated at the rated output voltage and rated PDS load:

- the total r.m.s. current of the converter output – I_{aN};
- the harmonic current spectrum of the converter output, including the fundamental – I_{aNh}, h is up to 40 or 50, this value shall be stated by the system supplier at the specified or typical output impedance (including motor and transformer if any), where needed, for system integration, see clause 9.

The rated output line-to-line voltage shall be stated at rated output current and rated PDS load:

- the total r.m.s. voltage of the converter output – U_{aN};
- the harmonic voltage spectrum of the converter output, including the fundamental – U_{aNh}, h is up to 25 or 40, this value shall be stated by the system supplier at the specified or typical output impedance (including motor and transformer, if any) where needed for system integration, see clause 9;
- the rise-time of the converter output voltage, where needed for system integration, see clause 9.

(U.S. Difference) Overload capacity of the converter is given in the table 1-4-1. It can be seen that the converter should be able to operate at rated maximum load (unlike the pds), because it has a low thermal time constant.

Table 1-4-1 *(U.S. Difference)*
OVERLOAD CAPACITY

As Percent of Rated Load	*110%*	*125%*	*150%*
Overload Duration	*60 sec*	*60 sec*	*60 sec*
Repetition Interval	*not less than 9 minutes*	*not less than 9 minutes*	*not less than 9 minutes*

6.2.3 Efficiency and losses

The definition of power conversion efficiency is given in 3.1.6.

Typically, efficiency is established by means of calculations or measurements or combinations of both (see clause 11).

(U.S. Difference) The parts of the equipment included in the determination of the converter efficiency shall be stated. For the definition of the converter alone, a guidance on the apparatus or components the losses of which are to be included or not, reference shall be made to the lists respectively included in 3.3.1 and 3.3.2 of IEC 60146-1-1. Losses in the d.c. link, due to d.c. reactors and/or capacitors, fuses (if any) and bus bars, not considered in 3.3.1 of IEC 60146-1-1, are a part of the total losses and shall be taken into account. In case of any doubt concerning whether the losses of a component of the converter equipment should be included or not when calculating the efficiency, it is to be stated whether such losses are included in the declared efficiency.

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6.3 TRANSFORMER

Transformers shall be rated to comply with the continuous output rating and overload capability of the converter assembly, as defined in 6.2.

Additional core losses due to voltage harmonics, as well as additional stray losses due to the higher frequency current harmonics shall also be considered.

Refer to clause 10 for additional details.

Voltage waveform characteristics including insulation requirements should be considered according to 8.2 and 8.4.

Transformers shall comply with IEC 60146-1-3.

6.4 MOTOR

6.4.1 Motor input ratings

The operating frequency and voltage range at the specified or typical output impedance (including motor and transformer if any) shall be provided by the system supplier using the following parameters:

- U_{AN1} = rated fundamental motor line to line voltage
- f_{min} = minimum frequency
- f_M = maximum frequency

Frequency and voltage ranges are defined by the system supplier. Harmonics and rise times of the line to line voltage at motor terminals shall be provided by the system supplier, see clause 9.

The motor currents shall be provided by the system supplier at rated motor voltage, base speed and rated PDS load:

- the total r.m.s. current of the motor (I_{AN});
- the fundamental and the relevant harmonic current spectrum of the motor (I_{ANh}) shall be stated at the specified or typical output impedance (including motor and if any, transformer and filters);
- the excitation current of the motor, if any;
- the auxiliary supply.

NOTE The additional losses due to the higher frequency current harmonics should be taken into account, if appropriate. The rated value assigned to the motor current, under the actual PDS operating conditions, may therefore account for some derating, compared with the rated motor current under sinusoidal supply.

6.4.2 Motor output ratings

The load envelope (see 3.1.4) should be agreed between system supplier, customer and driven equipment supplier. The capacity of the motor both for continuous and overload operation, shall comply with all required operating output conditions of the PDS.

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The rated motor power is the product of the maximum continuous output torque and the base speed. This does not necessarily correspond to the maximum power required by the load (system inertia included). In particular cases, an even larger motor rating could be selected to allow for severe overload conditions or current harmonic content.

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Section 7
CONTROL PERFORMANCE REQUIREMENTS

7.1 STEADY STATE PERFORMANCE

7.1.1 Steady state

The control system is in a steady state when the reference and operating variables have been constant for more than three times the settling time of the control system and the service variables have been constant for more than the three times the longest time constant of the equipment (for example the thermal time constant of the speed sensor). Steady state performance for drive variables such as torque, speed, position, etc. shall be specified in accordance with 7.1.2 et 7.1.3.

7.1.2 Deviation band

The deviation band (see figure 11) is the total excursion of the directly controlled variable (unless another variable is specified) under steady state conditions as a result of changes in the service or operating conditions within their specified ranges.

The deviation band is expressed:

a) as a percentage of the ideal maximum value of the directly controlled (or other specified) variable, see example in 7.1.3;

b) as an absolute number for variables which have no readily definable base, such as position

If not otherwise agreed upon between the system supplier and the customer, the signal representing the directly controlled variable should be filtered by a first order low-pass filter with a 100 ms time constant in order to remove noise and ripple from the signal.

NOTE The deviation band cannot be used to specify items which are not related with the steady state control performance (for example torque pulsation, see 8.4.4.4, or the speed ripple caused by load torque or motor torque pulsation, see 7.2.2.6).

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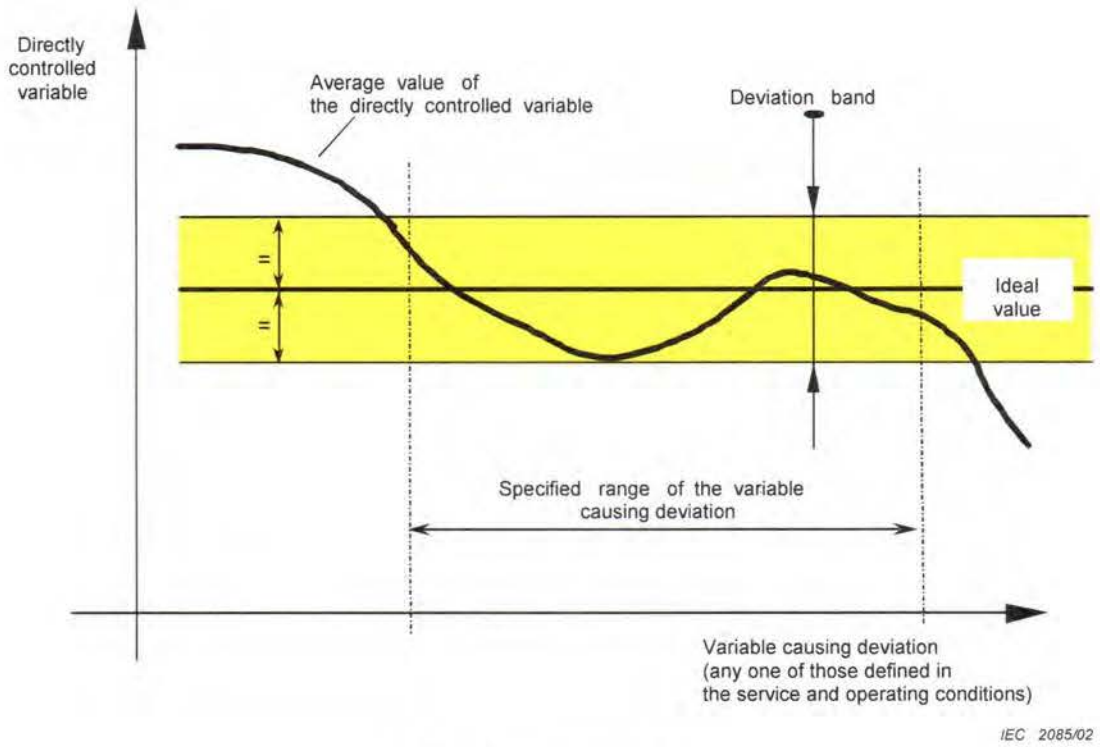


Figure 11 – Deviation band

7.1.3 Selection of deviation band (steady state)

The steady state performance of a feedback control system shall be described by a number, selected from table 6 (other levels may be defined by agreement).

The range of variables to which the deviation band apply shall be specified (see figure 11).

Table 6 – Maximum deviation bands (percent)

±20	±10	±5	±2	±1	±0,5	±0,2	±0,1	±0,05	±0,02	±0,01

EXAMPLE: A drive has a 60 Hz 1 780 r/min motor that is fed by a frequency converter. The maximum speed of the drive is 2 000 r/min and the specified deviation band for the speed control is ±0,5%. Operating conditions are, speed range: 0 to 2 000 r/min; load torque range: zero to rated torque. Service conditions, ambient temperature range: +5°C to +40°C.

Thus, the deviation of the actual speed from the ideal value (speed reference) is:

±0.5% of 2 000 r/min = ±10 r/min

when the value of the speed reference, load torque and ambient temperature are within their specified ranges.

For example if the speed reference is 1 200 r/min, the actual speed of the motor will be 1 200 ± 10 r/min, that is between 1 190 r/min and 1 210 r/min.

7.2 DYNAMIC PERFORMANCE

7.2.1 General

Drives shall be provided with either a current limit or a timed acceleration.

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If dynamic performance is considered important (see annex B), the specification shall be agreed upon between the customer and system supplier by using the following definitions.

7.2.2 Time responses

7.2.2.1 Overview

Time response represents the output versus time curve resulting from the application of a specified input, under specified operating and service conditions (see 10.3.4).

If not otherwise agreed upon between the customer and system supplier, the drive shall operate before the application of a specified input under the following operating and service conditions:

- base speed;
- no load;
- rated system voltage and frequency;
- temperature stabilized after a 1 hr warm-up of the measuring equipment and interfaces, ambient temperature being within service conditions.

The output curve may contain a significant amount of ripple, for example due to the operation of the semiconductor devices in the converter. The average curve shall be used in the determination of the time response, see figure 12, if not otherwise agreed upon between the system supplier and customer.

Typical time responses for a drive system are the time responses following a step change of speed reference, current reference or torque reference, figure 12, and the time response following a change in the load torque, figure 13. For specification purposes, the load torque of the driven equipment shall be assumed to increase linearly from zero to a specified torque (or decrease from a specified torque to zero) within 100 ms, without overshoot, if not otherwise agreed between the system supplier and customer.

7.2.2.2 Response time

The response time is the time required, following the initiation of a specified stimulus to a system, for an output going in the direction of the necessary corrective action to first reach a specified value.

The specified value for a time response following a step change of reference input, see figure 12, shall be the initial average value plus 90% of the steady state increment. The transient overshoot shall be equal to or less than 10% of the steady state increment if not otherwise agreed upon between the system supplier and customer.

For a time response following a change in an operating variable, figure 13, the specified value shall be the final average value plus 10% of the maximum transient deviation.

7.2.2.3 Rise time

The rise time is the time required for the output of a control system to make the change from a small specified percentage of the steady-state increment to a large specified percentage of the steady-state increment, either before overshoot or in the absence of overshoot (see figure 12).

The small specified percentage shall be 10%, the large specified percentage shall be 90% and the transient overshoot shall be equal to or less than 10% of the steady state increment if not otherwise agreed upon between the system supplier and customer.

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If the term "rise time" is unqualified, response to a step change is understood. Otherwise, the pattern and magnitude of the stimulus should be specified.

7.2.2.4 Settling time

The settling time is the time required, following the initiation of a specified stimulus to a system, for a specified variable to enter and remain within a specified narrow band centered on its final average value.

For a time response following a step change of reference input, see figure 12, the specified band shall be ±2% of the steady state increment, if not otherwise agreed upon between the system supplier and the customer.

For a time response following a change in an operating variable, see figure 13, the specified band shall be ±5% of the maximum transient deviation, if not otherwise agreed between the system supplier and the customer.

7.2.2.5 Load impact speed deviation area

Load impact speed deviation area (corresponding to a drift of the position) provides an assessment of the response of a speed control for a sudden change in load torque (see figure 13). The formula is the following:

$$\frac{\text{response time} \times \text{maximum transient deviation}}{2}$$

where the maximum transient deviation is given as a percentage of the maximum operating speed. Thus, the unit of the load impact speed deviation area is percent seconds (%s).

7.2.2.6 Torque amplification factor (TAF)

Torque amplification factor is the ratio

$$TAF = \frac{M_P - M_{ini}}{M_{inc}}$$

where M_p is the peak torque encountered in the shaft system after a sudden increase in the load torque by the amount M_{inc}, and M_{ini} is the initial torque before the torque increase.

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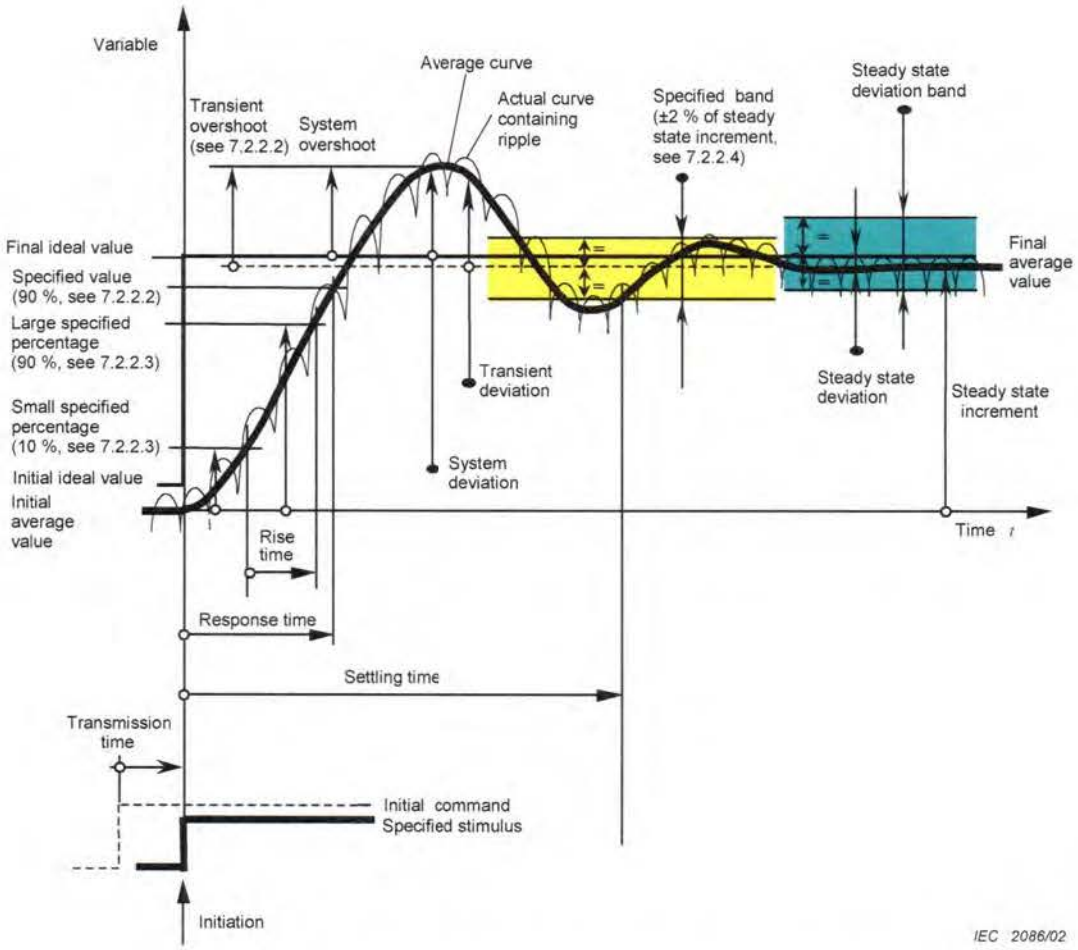


Figure 12 – Time response following a step change of reference input – no change in operating variables

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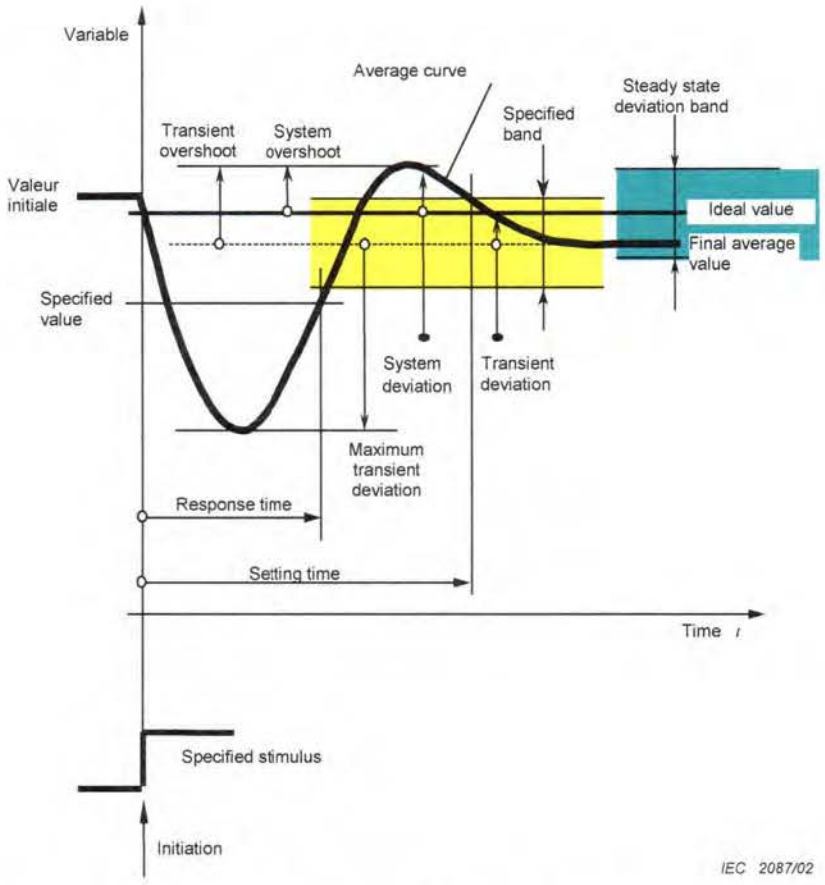


Figure 13 – Time response following a change in an operating variable – no reference change

7.2.2.7 Dynamic deviation

Dynamic deviation is the deviation between the reference (ideal value) and actual value when the reference is changed at specified rate (see figure 14).

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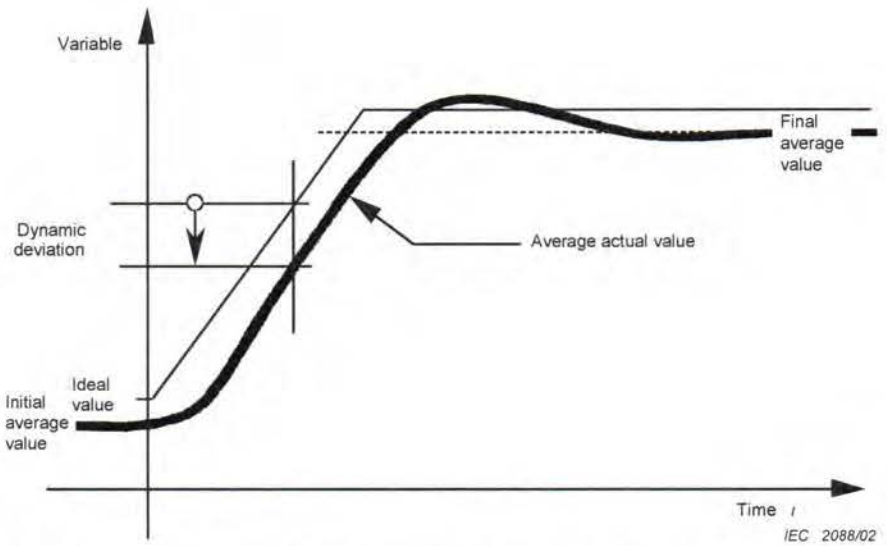


Figure 14 – Time response following a reference change at specified rate

7.2.3 Frequency response of the control

7.2.3.1 Frequency analysis

Frequency response represents the amplitude ratio (amplification) and phase difference between the controlled variable and the sinusoidal stimulus as a function of the stimulus frequency when the feedback loop (if it exists) is closed.

NOTE 1 It is possible to use multi-frequency stimulus (noise) instead of the sinusoidal variable frequency stimulus when the frequency response is measured by using a frequency analyzer.

NOTE 2 It is common to use decibels (dB) with the amplification, see IEC 60027-3. The formula is:

$$G = 20 \log_{10}\left(\frac{F_2}{F_1}\right) \text{dB}$$

where F_2/F_1 is the amplitude ratio and G is the gain. For example, if the amplitude ratio is 0,708, the gain is approximately –3 dB.

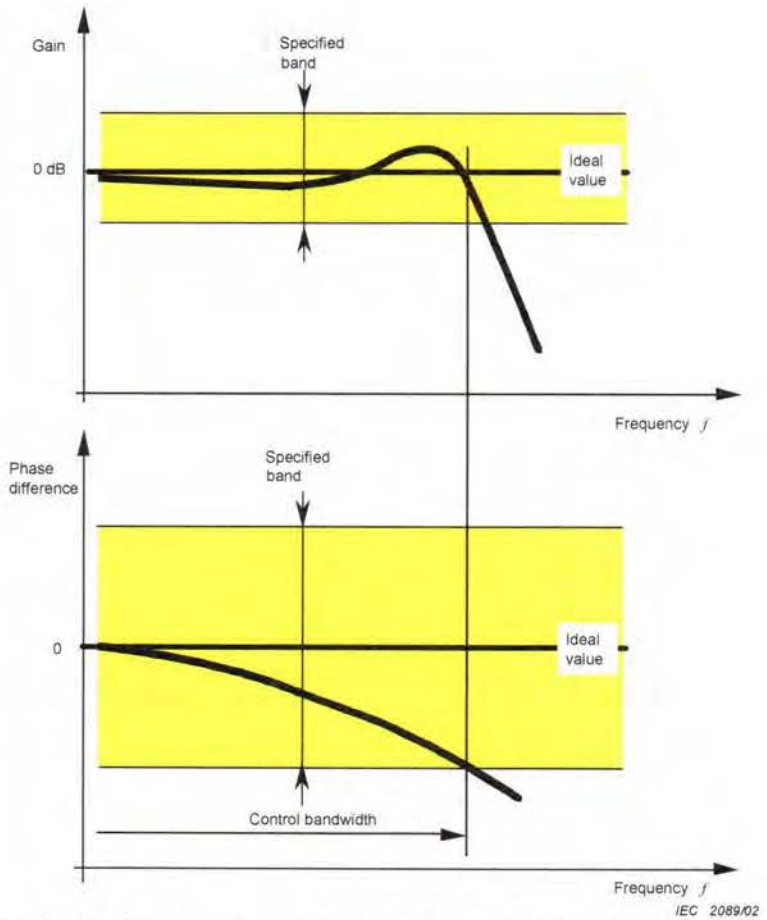
7.2.3.2 Control bandwidth

The control bandwidth is the frequency interval where both the amplification (gain) and phase difference of the frequency response with the reference variable as a stimulus remain within specified bands centered on 0 dB and 0 degrees values, respectively, see figure 15. The specified bands shall be ±3 dB and ±90 degrees if not otherwise agreed between the system supplier and customer.

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NOTE The control bandwidth of the case shown in the figure is limited by the specified phase band.

Figure 15 – Frequency response of the control – reference value as stimulus

7.2.3.3 Disturbance sensitivity

The disturbance sensitivity is the frequency response amplification when the stimulus is a specified operating variable. Typical example is the sensitivity of the motor speed for pulsating load torque, see clause B.3.

NOTE The sensitivity may be expressed in dB only when both the controlled variable amplitude and the stimulus amplitude are expressed in per unit (p.u.).

7.3 PROCESS CONTROL INTERFACE PERFORMANCE

7.3.1 General

The process control interface and its performance has to be defined and agreed upon between the system supplier (see 8.1) and the customer in as early a stage as possible. The following list shall be used for the definitions.

7.3.2 Analog input performance

The items specified may include, but are not limited to, the following:

– number of analog inputs;

– type of analog input, for example

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  - single-ended voltage input,
  - differential voltage input,
  - current loop input;
- isolation voltage level of the input;
- input voltage or current range depending on the input type;
- input impedance;
- time constant or bandwidth of the hardware low-pass filter;
- gain and offset errors;
- resolution of the A/D converter, if it exists;
- sampling interval of the A/D converter, if it exists.

NOTE For a more complete list see IEC 61131-2.

7.3.3 Analog output performance

The items specified may include, but are not limited to, the following:

- number of analog outputs;
- type of analog output, for example
  - single-ended voltage output,
  - differential voltage output,
  - current loop output;
- isolation voltage level of the output;
- output voltage or current range depending on the output type;
- maximum load;
- time constant or bandwidth of the hardware low-pass filter;
- gain and offset errors;
- resolution of the D/A converter, if it exists;
- conversion interval of the D/A converter, if it exists.

NOTE For a more complete list see IEC 61131-2.

7.3.4 Digital input performance

The items specified may include, but are not limited to, the following:

- number of digital inputs;
- type of digital input, for example
  - relay input,
  - optocoupler input;
- isolation voltage level of the input;
- rated control voltage and type (a.c. or d.c.);
- input resistance;
- propagation delay of the input.

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7.3.5 Digital output performance

The items specified may include, but are not limited to, the following:

- number of digital outputs;
- type of digital output, for example
  - relay output, normally open contact,
  - relay output, normally closed contact,
  - transistor output, normally open;
- isolation voltage level of the output;
- maximum voltage and type (a.c. or d.c.);
- maximum current and type (a.c. or d.c.);
- operation delay of the output;
- propagation delay from input to output.

NOTE For a more complete list see IEC 61131-2.

7.3.6 Performance of communication links

The items specified may include but are not limited to the following;

- number of communication links;
- type of communication link, for example
  - commissioning and maintenance link,
  - automation system link;
- type of the physical interface (connector and cable type);
- protocol used;
- maximum data transfer rate in bits per second;
- maximum length of the cable that can be connected to the link;
- maximum number of links that can be connected to the same communication cable or communication bus system.

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Section 8
PDS MAIN COMPONENTS

8.1 RESPONSIBILITIES

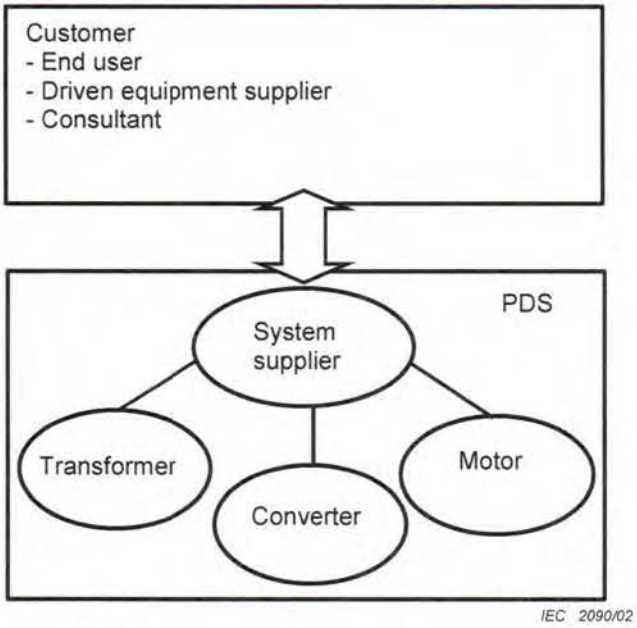


Figure 16 – Responsibilities of the system supplier

The system supplier is typically responsible:

- for the clarification and agreement on the external interfaces of the PDS with the customer (see clause 7 and clause 9);
- for the clarification and agreement on the PDS performance specification with the customer (see clause 7 and clause 9), and the acceptance criteria for testing;
- for the clarification and agreement with the component manufacturers, on the specifications of the main components of the drive system (transformer, converter, motor, see clause 8) and the acceptance criteria for testing.

The driven equipment supplier is typically responsible for the mechanical string. In critical cases (see 9.4), it is recommended to establish a direct communication between the system supplier and the driven equipment supplier.

The system supplier is responsible for the organization of the necessary co-operation between converter, assembler, driven equipment and motor-specialists.

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8.2 TRANSFORMER

8.2.1 Introduction

LINE SIDE INTERFACE (U.S. Difference)

The term line-side interface encompasses transformers or reactors where used between the line and the power converter of an adjustable-speed drive. Transformers (isolation and auto) may be used both on the input and output of adjustable-speed drive converters. Such transformers are not normally essential for converter operation but are intended to satisfy one or more of the following requirements:

a. Meet local codes
b. Provide galvanic isolation
c. Establish voltage levels
d. Establish grounding requirements
e. Reduce short-circuit fault current levels
f. Provide transient suppression
g. Reduce harmonic content of input currents
h. Reduce motor-to-ground voltages

The transformers are subjected to harmonic waveforms.

This subclause addresses transformers and reactors in the main power path of the power drive system (PDS). Transformers can be used at the source (power system) end of the PDS or at the load (motor) end of the PDS. The purposes of transformers include:

- voltage matching;
- isolation;
- harmonic cancellation.

Standard transformer construction types which are applied in PDS are dry-type and liquid-filled coil. These requirements are intended to assure the suitability of transformers for drive system duty.

The fundamental rating of the transformer should be in accordance with IEC 60146-1-3.

Transformers supplied as part of the PDS shall be properly rated to meet the requirements:

- of the steady state load;
- any momentary overloads.

For drive systems that normally run in adjustable speed mode, the transformer should be rated to deliver the required power on a steady state basis. Periodic overloads can be used to calculate a r.m.s. apparent power (kVA) loading for the transformer.

8.2.2 Specification and rating

8.2.2.1 Harmonic currents and voltages

Converter modules cause harmonic currents and voltages, which cause an additional stress for the connected transformers (thermal, insulation). The transformer design shall take special care of the following:

- additional winding losses of each winding;

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- additional iron core losses;
- additional insulation requirements (including common mode voltages and increased voltage stress).

In cases where the converter is filtered sufficiently on the valve side of the transformer, the use of standard transformers may be considered, assuming allowance is made for common mode voltages (insulation requirements).

8.2.2.2 Winding arrangement

Annex D of IEC 60076-1, contains the most common transformer winding arrangements and connection symbols.

The requirements (for example phase shift, winding arrangement, impedances) shall be clearly stated for the transformer design and installation purposes.

8.2.2.3 Phase offset requirements

The harmonic attenuation effects to be achieved by multi-pulse transformer and converter circuits depend on the accuracy of the phase shift between the windings. The phase shift between the windings are specified at the fundamental frequency. Errors in the fundamental phase shift result in a much higher error at the harmonic frequency than at the fundamental frequency.

For example a 2° error in phase shift for the fundamental of a 12 pulse PDS results in a phase error of $(5 + 1)° \times 2° = 12°$ for the 5^{th} and $(7 - 1)° \times 2° = 12°$ for the 7^{th} order harmonics. The corresponding residual values in case of a current source converter are:

$$\frac{I_5}{I_1} = \frac{1}{5} \times \sin\left(\frac{12°}{2}\right) = 0{,}021 \quad \text{and} \quad \frac{I_7}{I_1} = \frac{1}{7} \times \sin\left(\frac{12°}{2}\right) = 0{,}015$$

For cancellation of higher harmonics, a 15° phase shift is used with extended delta or zigzag windings. In such cases, it is the 11th harmonic that is of most interest and a 2° phase error has a much higher impact.

The resulting phase error should be kept below 2° of fundamental period for a 12 pulse transformer, including phase error of the transformer windings and eventually the thyristor control system.

8.2.2.4 Rating plate requirements

The following requirements are based on the requirements of 7.1 of IEC 60076-1. The information listed is to be provided in addition to the rating plate data of 7.1 of IEC 60076-1.

a) Type of transformer (for example, converter supply transformer, converter output auto-transformer, etc.) as description of the function of the transformer in the PDS.
b) Number of phases on input and output. Alternatively, the number of three-phase windings on input and output of the transformer.
c) Rated frequency range, if variable.
d) Rated voltage range, if variable.
e) Connection symbol, or phase offsets listed in degrees.

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8.2.2.5 Ambient requirements

Temperature requirements according to IEC 60146-1-3:

- ambient: 40°C
- daily average: 30°C
- yearly average: 25°C

8.2.3 Impedances

8.2.3.1 General

The input transformer impedances shall be coordinated in regard to harmonic emission and fault current requirements, typically the impedance is in the 6% to 12% range (often according to IEC 60076).

8.2.3.2 Commutating reactance

Commutating reactance is an important parameter for line commutated converters. Measurement methods for commutating reactance are given in 5.1.1 of IEC 60146-1-3.

8.2.3.3 Impedance with self-commutated converters

Commutating reactance has less impact on the performance of self-commutated converters. However, transformer impedance may be important to limit harmonic currents or fault currents. For self-commutated converters, the impedance is usually taken to be the short-circuit transformer impedance measured in standard transformer tests. See 10.4 of IEC 60076-1. Measuring the short-circuit impedance at the frequency of interest may also be advisable.

8.2.4 Common mode and d.c. voltages

8.2.4.1 General

Any operating condition of a power converter that can place unusual voltage conditions on the transformer windings shall be identified by the transformer supplier. Some types of converters can impose voltage offsets on input or output transformers. Two common problems caused by voltage offsets are:

- increased insulation stress due to common mode voltages;
- core saturation due to d.c. voltage or d.c. current magnetization.

8.2.4.2 Insulation stress due to common mode voltages

The most common mechanism for increased insulation stress is for the neutral of the winding connected to the converter to be offset from the ground, as the switches in the converter are gated. This common mode voltage will impose a higher than normal stress on the transformer insulation. The common mode voltage should be taken into account in specifying the insulation level of the transformer, either by specifying the common mode voltage explicitly (preferred) or by specifying the appropriate insulation level for the affected winding.

Additional voltage stresses due to fast voltage rise time and voltage reflections (including power cable) should be considered too in the specification of the needed insulation voltage level.

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8.2.4.3 Core saturation due to d.c. components

Converters can create voltages or currents that can lead to saturation of a connected transformer core, either at the input or the output. The transformer designer shall be informed of the amount of d.c. voltage or d.c. current that may be imposed on the transformer so that the design can be made to operate appropriately. Low flux density core designs and gapped cores may be necessary.

In the case of series coupled converters, the addition of d.c. offset voltage of each converter should be considered.

8.2.5 Specific requirements

8.2.5.1 Cooling systems

According to IEC 60076-1 and IEC 60726.

8.2.5.2 Noise requirements

Due to non-sinusoidal currents and voltages, an increased level of noise emission is to be expected.

Limitations for noise emission levels and eventually necessary secondary noise reduction measures have to be specified and agreed upon between transformer manufacturer, system supplier and customer. Unless otherwise specified, measurement methods for transformer noise emission should be in accordance with IEC 60076-1.

8.2.5.3 Voltage accuracy

According to IEC 60076.

8.2.5.4 Parallel connection of bridges

Special attention shall be given in case of parallel connection of bridges (accuracy of no-load voltages, phase shift, short-circuit impedance of each secondary winding).

8.2.5.5 Shielding between primary and secondary winding

An electrostatic shield is recommended in order to prevent high voltage transients being transferred to the secondary due to capacitive coupling. The shield also has an EMC effect on the common mode impedance for conducted disturbances. For both reasons, the inductance of the shield connection to earth should be low.

8.2.5.6 Short-circuit requirements

Converters make the possibility of short circuits on transformers more likely than in normal duty. The designer shall understand the risk of short circuit in the frequency converter and design the transformer for the appropriate short-circuit level and frequency of occurrence.

8.3 CONVERTER AND ASSOCIATED CONTROLS

8.3.1 Object

The object is to cover the performance and requirements of the converter, which is a part of the PDS. It consists of the converter section (which may include input and output filters), converter controls, protection and auxiliaries. Reference is made in general to IEC 60146.

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8.3.2 Design requirements

8.3.2.1 Degree of protection

The protection class definition shall be according to IEC 60529.

8.3.2.2 Corrosive environments

If pollution degree 2 is exceeded, adequate measures should be taken to ensure that the converter environment remains non-corrosive. A positive pressure of clean air in the converter environment should be maintained or appropriate scrubbers should be used.

8.3.2.3 Cooling

8.3.2.3.1 General

The three common types of cooling are forced air, de-ionized liquid and evaporative cooling. The converter manufacturer shall have the responsibility to adequately design the cooling system taking into the account the working voltages, currents, and duty cycle. *(U.S. Difference) Redundancy is recommended for critical applications. Availability can be enhanced by designing the adjustable-speed drive system with redundancies, which can be provided at the component level, subassembly level, and at the system level.*

8.3.2.3.2 Air cooling

Air filtering shall be provided if the cooling air supply contains particles that could be damaging to the converter cooling paths.

8.3.2.3.3 Liquid cooling

In the case of liquid cooled converters, the cooling media shall have a sufficiently high resistivity to limit the leakage current to ground and between different potentials of components to a safe and non-destructive level. The resistivity shall be monitored and result in an alarm or trip for low and very low resistivity. Monitoring of flow, reservoir level and water temperature is highly recommended to provide adequate protection. Special care should be exercised to limit electrolytic currents due to material mismatches, for example aluminum and copper shall not be used in the same cooling circuit.

8.3.2.4 Acoustic noise

The noise level measured at 1 m shall be below 85 dBA, unless otherwise agreed between customer and manufacturer. Compliance to more stringent local regulations shall be agreed upon between the system supplier and customer.

8.3.2.5 Power connections

All power connections shall be provided with adequate working area and mechanical stress relief support points shall be provided. Shield ground connection points shall be provided in the vicinity of power connections when shielded cable is used.

8.3.2.6 Protections

Converter protection shall be according to 9.3.

Main power terminals shall be clearly marked in accordance with IEC 60146-1-1.

Rating plates shall be according to IEC 60146-1-1 and IEC 60146-2.

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Storage and transportation shall be according to 5.2 and 5.3 due to the delicate nature of the converters. The converter manufacturer shall supply special instructions outside those specified.

8.4 MOTOR

8.4.1 Introduction

The system designer shall ensure, that in all practical conditions of operation, the stress level does not exceed the motor withstand capability, and establish agreement on the verification procedure.

The most common a.c. motors used in PDS above 1 kV are covered in this subclause. Motor construction can consist of general purpose standard design as well as special application orientated. In addition to standard motor designs, new technologies, for example permanent magnet motors and other special solutions are also considered.

In this field of application, many different types of motors exist. Most are induction and synchronous motors. The number of phases are typically three or six. Most of them are triple multiple phase numbers.

Requirements for commonly used motors are covered in the relevant product standard of IEC 60034. This subclause considers the integration and interfacing of the motor as a part of the PDS.

8.4.2 Design requirements

Unless otherwise specified, the enclosure shall be in accordance with IEC 60034-5.

Unless otherwise specified, the cooling system shall be in accordance with IEC 60034-6.

Unless otherwise specified, mounting shall be in accordance with IEC 60034-7.

Special attention is required because the speed dependency on heat transfer of self-ventilated cooling systems and additional harmonic losses in inverter fed motor operation (see IEC 60034-17).

Unless otherwise specified, ambient and cooling temperatures, thermal class and temperature rise of the motor winding insulation system in inverter fed conditions should be in accordance with IEC 60034-1.

8.4.3 Performance requirements

The operating characteristics under normal converter fed operation are defined in 6.2.2 and 6.4.2.

In the case of 3-phase motors, occasionally a direct bypass operation to the line-side or transformer secondary side may be required (see 4.4). A motor partial-winding operation in the case of a winding system with a multiple of 3 phases is also conceivable.

Performance and rating conditions for such a bypass operation shall be clearly defined by the customer, especially for:

– necessary starting performance;

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– eventually different rated torque.

8.4.4 Mechanical system integration requirements

8.4.4.1 Protection against destructive shaft voltages or bearing currents

Unless otherwise agreed upon between the system supplier and the customer, the motor should be supplied with bearing insulation at the non-driven end.

In addition to the recommended earthing practice (see 9.2.3), other preventive measures may be necessary (see 9.2.4.6). They are especially needed when high frequency components exist in the motor voltage, including common mode voltages, caused by the converter.

8.4.4.2 Acoustic noise emission

Compared to line fed operation, converter feeding of the motor leads to increased noise emission (see IEC 60034-17). The manufacturer of the motor shall give the expected value of noise when the motor is converter fed for the intended use.

Limitations for noise emission levels and eventually necessary secondary noise reduction measures have to be specified and agreed upon between system supplier and customer. Unless otherwise specified, the measurement methods for motor noise emission should be in accordance with IEC 60034-9.

8.4.4.3 Motor-vibrations and lateral resonance

Unless otherwise specified, the permitted limits of vibration severity and method of measurement should be as defined in IEC 60034-14.

In this context, clear responsibilities relating to a correct motor fastening (foundation, mechanical string alignment and coupling) between driven equipment supplier, motor-manufacturer and system supplier should be defined and agreed. Special attention should be given to the lateral resonance frequencies of the whole mechanical string (see 9.4).

8.4.4.4 Torque pulsations and torsion considerations

Torque pulsations are electromagnetically produced as a result of voltage and current harmonics in a converter fed motor.

TORQUE PULSATIONS (U.S. Difference)

The knowledge of the harmonic content of motor voltages and currents is also important in determining the pulsating torques excited by harmonics. Typically, large adjustable-speed drives use a basic six-pulse-modulated inverter or a multiplicity of six-pulse-modulated inverters appropriately phase-shifted to reduce harmonics.

MECHANICAL CONSIDERATIONS (U.S. Difference)

The converters covered by this annex generate a spectrum of harmonic currents in the motor stator circuit. These harmonic currents then interact in the motor to produce mechanical torques on the shaft and reaction torques on the frame. These torque harmonics can excite further natural frequencies in the mechanical system which may cause higher than normal vibration or mechanical failure. If this occurs, remedial design changes should be made to the system.

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TORSIONAL CONSIDERATIONS (U.S. Difference)

With motors designed to be used at constant speed, there may be mechanical resonances which will be excited at other than design speed. The motor vibration should be checked over the operating speed range to assure trouble-free operation in the adjustable-speed range.

Disturbing or dangerous influences on mechanical structure elements, such as excitation of torsion resonances of the motor and driven equipment, shall be avoided during normal operation and under fault conditions.

Necessary analyses and corrective actions have to be defined and managed by the system supplier and have to be undertaken in close cooperation between converter, motor and driven equipment experts (see 9.4.2), during the design process.

8.4.5 Voltage stress of the motor winding insulation system

8.4.5.1 Responsibilities

MOTOR INSULATION SYSTEM (U.S. Difference)

The insulation system of the motor may be subjected to higher dielectric stresses than in the case of supply with sinusoidal voltages and currents. These dielectric stresses occur due to increased peak voltages, motor neutral-to-ground voltage, and rate of change of voltage.

The system designer shall ensure, that in all practical conditions of operation, the voltage stress level does not exceed the insulation system voltage stress capability (see 8.4.5.2 and 8.4.5.3). Therefore, the system designer is responsible for specifying the voltage stress level at the motor terminals, taking into account possible voltage reflection depending on the topology of the converter, cable type and length, etc. Relevant parameters for insulation stress are: transient peak voltage values, peak rise time, repetition rate, etc.

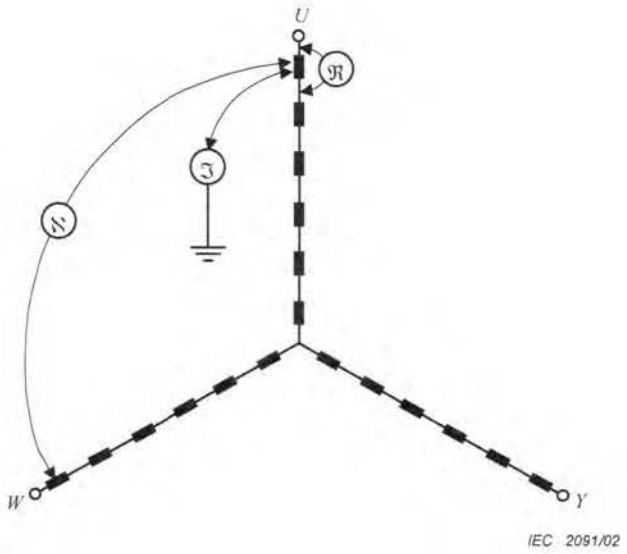
The motor manufacturer shall check the voltage stress withstand capability according to the system supplier's specification. To ensure that no service lifetime reduction of the motor insulation occurs, the actual stress due to converter operation shall be lower than the repetitive voltage stress withstand capability of the motor winding insulation system (see 8.4.5.2 and 8.4.5.3).

8.4.5.2 Types of winding stresses and limiting figures

Three different insulation stresses exist (see figure 17).

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① main insulation line to line
② main insulation line to frame
③ inter-turn insulation in first coil

Figure 17 – Insulation stressing types

In line fed motors (sinusoidal, low frequency) the most occurs in the line to line and line to frame insulation. The electric stress of the inter-turn insulation is relatively low, however in the case of converter fed motors it can become very important and increased attention is necessary.

In a converter fed operation, the motor voltage is non-sinusoidal, typically with repeated transient voltage steps caused for example, by fast switching PWM-inverters with relatively high pulse frequencies or by load side commutation notches of a thyristor inverter (see A.2.5). In case of PWM voltage source inverter with motors fed via relatively long cables, each transient voltage step leads to reflections at the motor and the converter terminals with typically oscillating voltage overshoots (figure 18).

t_a is the peak rise time of the voltage step (including the mentioned reflection phenomena). Definition of t_a is given in IEC 60034-17 as the time for the voltage to change from 10% to 90% of the total transient voltage ΔU including overshoot (see figure 18).

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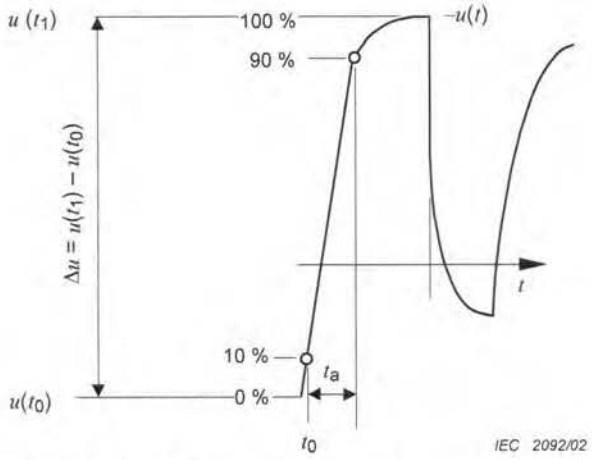
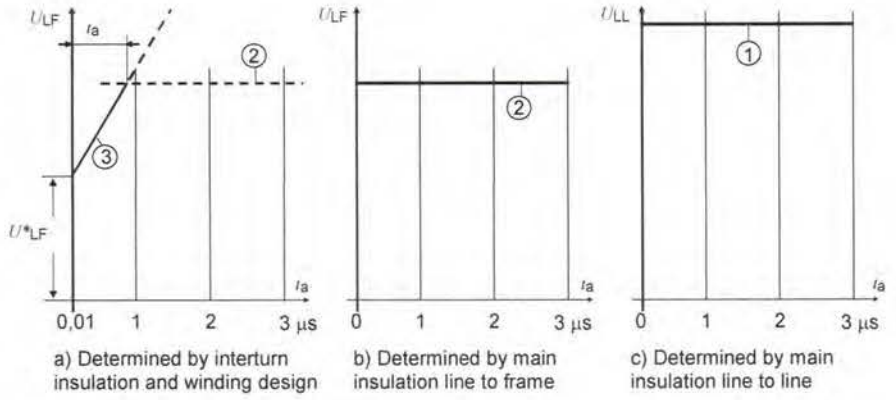


Figure 18 – Definition of the transient voltage at the terminals of the motor

The repetitive voltage stress withstand capability of the winding insulation system without service lifetime reduction can be described by the border lines given in figures 19a, 19b, and 19c. These borderlines refer to the admissible pulse voltage, including voltage reflections at the motor terminals.



The numbers in these figures are common references to figure 17 and to table 7

IEC 2093/02

Figure 19 – Admissible pulse voltage (including voltage reflection and damping) at the motor terminals as a function of the peak rise time t_a

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Figure 19 represents:

- inter-turn stressing type δ relevant for transient voltage steps ΔU_{LF} with typical peak rise time $t_a \leq 1$ µs (figure 19a);
- voltage differences up to the withstand capability of the main insulation according to figure 19b for line to frame stressing type σ;
- voltage differences up to the withstand capability of the main insulation according to figure 19c for line to line stressing type α.

8.4.5.3 Typical voltage stresses capability of motors with usual design

Deriving from the insulation stress at line operation with usual voltage tolerances, the usual design of high voltage motors gives at least a withstand capability indicated in the right column of table 7. These formulae are given for guidance, if no further information is available from the motor manufacturer and represent minimum values. Significant higher voltage limitations are often proposed.

Table 7 – Limiting parts and typical voltage stress capability of the motor insulation system

Limiting part of Insulation system	Relevant peak voltage value	Voltage stress capability of 3-phase motors
① Main insulation, phase to phase	• U_{LL} line to line • voltage difference	$U_{LL} = 1{,}1 \ U_{Ins}\sqrt{2} \approx 1{,}6 \ U_{Ins}$
② Main insulation phase to frame	U_{LF} line to frame max. voltage difference	$U_{LF} = 1{,}1 \ U_{Ins} \sqrt{2/3} \approx 0{,}9 \ U_{Ins}$
③ Inter-turn insulation of first coil	ΔU_{LF} voltage step t_A associated peak rise time (see figure 18)	ΔU_{LF} at least 3 kV $t_a \approx 1$ µs see figure 19a

U_{Ins} is the rated r.m.s. voltage value of motor insulation system.

NOTE 1 The "rated voltage of insulation system" U_{Ins} (shown in table 7) is not necessarily equal to the "rated motor voltage" U_A as given in 3.1.20.

NOTE 2 In the case of inverter fed motors, it is often appropriate to use a motor design with improved insulation systems having $U_{Ins} > U_A$ (motor) .

NOTE 3 As figure 19a shows, the inter-turn insulation of the first coil is the limiting part for permissible transient voltage steps ΔU_{LF} in case of relatively short peak rise times in the range

0,1 µs $\leq t_A \leq$ 1 µs.

For $t_A >$ 1 µs the relevant limitations are normally given by the main insulation (figures 19 b and 19c).

NOTE 4 Because the switching of semiconductor elements in each phase occur at different times, the line to line voltage and the line to frame voltage have corresponding transient voltage steps $\Delta U_{LL} = \Delta U_{LF}$.

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8.4.5.4 Functional evaluation of motor winding insulation systems

Test procedures for winding insulation systems used in motors of rated voltage above 1 000 V should be in accordance with IEC 60034-18-31. Special attention is required, because of the additional stress factors produced by the converter fed operation such as increased voltage stress and high frequency repetition rate, additional heating as a result of harmonic losses (see 11.2.4.4) and mechanical vibrations (see 9.4).

THERMAL CONSIDERATIONS (U.S. Difference)

The temperature of the motor will be affected by power losses caused by harmonic currents and reduced cooling from shaft mounted fans at operation below rated speed. The system design should allow for these conditions. In those applications requiring a continuous overload capacity, the use of a higher horsepower rated motor is recommended.

8.4.6 Designation of essential data

The following information shall be supplied in addition to the normal rating plate of the motor:

- rated torque;
- torque at minimum speed;
- lowest speed at rated torque;
- minimum speed;
- base speed;
- maximum speed.
- *low speed motor data (U.S. Difference)*

MOTOR PARAMETERS FOR ADJUSTABLE-SPEED DRIVE OPERATION (U.S. Difference)

It is recognized that the user may sometimes wish to purchase a converter and use an existing motor. In this event, the motor supplier may be asked to supply certain parameters at other than base frequency. Among these are:

a. Stator inductance at low frequency—L_1
b. Rotor inductance at low frequency—L_2
c. Magnetization inductance at low frequency—L_m
d. Stator resistance—R_1
e. Rotor resistance at low frequency—R_2

The effect of temperature on these parameters may also be required.
In addition, the optimum values of voltage boost at low frequency might be requested. The intent is to determine the levels of voltage or current boost (at other than base frequency) for the converter, such that the desired performance at other frequencies (including starting torque) can be realized.

The following additional information is necessary for a proper system design and installation of the motor, and shall be supplied separately, for example in the product documentation:

- rotor moment of inertia and if required, motor shaft stiffness for torsion investigations according to 8.4.4.4 and 9.4;
- additional insulation system data such as rated voltage V_{ins} in accordance with 8.4.5.3 or alternative information about voltage stress, and withstand capability;
- direction of rotation, and limit if any;
- air flow and surrounding requirements for motor cooling system;

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- motor impedances (if required);
- relevant mounting dimensions;
- the shaft, the dimensions and the balancing should be in accordance with ISO/IEC, unless otherwise specified, "half key balancing" is relevant;
- mass of motor (rotor, stator);
- instructions for transportation, handling and storage;
- safety and maintenance instructions.

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Section 9
PDS INTEGRATION REQUIREMENTS

9.1 GENERAL CONDITIONS

9.1.1 Overview

In general, the PDS consists of the following main subsystems:

- transformer;
- converter section;
- control and protection;
- motor;
- harmonic filters (if needed).

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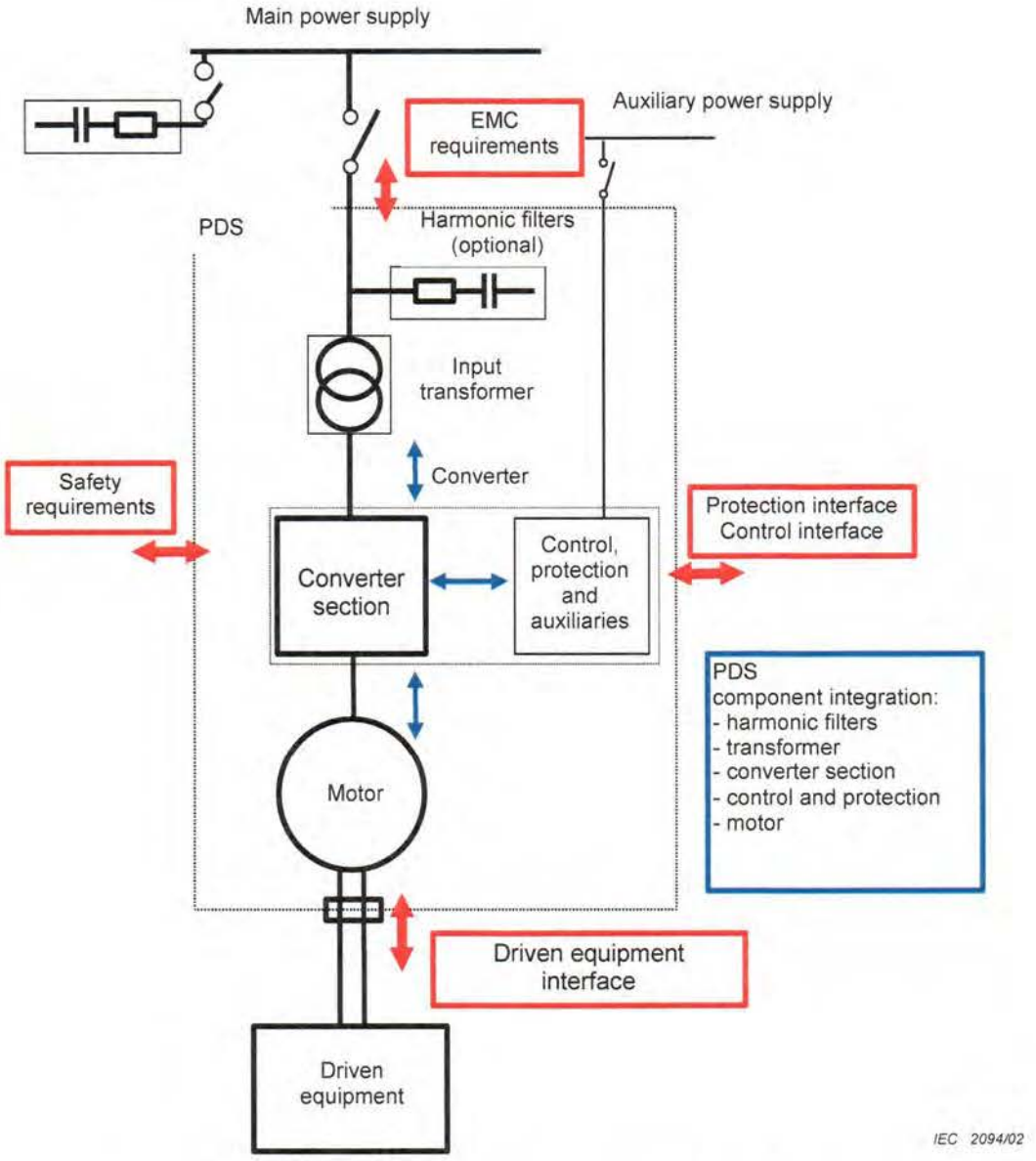


Figure 20 – Power drive system (PDS) – voltage above 1 000 V

9.2 SPECIAL CONDITIONS

9.2.1 Interactions between drive components

The installation of the PDS, consisting of its main components, in the location where it is intended to be used, requires a certain amount of know-how regarding both the correct operation of the PDS itself, and the interaction within its local environment. For a PDS whose voltage exceeds 1 kV a.c., special attention should be paid to the integration into the environment, in particular:

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- the main power supply;
- the main breaker;
- the main power cables;
- the EMC immunity and emissions;
- the civil installation;
- the driven machine;
- the auxiliary power supply;
- the main process control.

Within the PDS, special attention shall be paid to the interfaces and interference of the different subsystems in regard to:

- the system dimensioning;
- the safety requirements;
- the EMC according to internal requirements and IEC 61800-3;
- the possible interaction of subsystems.

The system supplier shall give all necessary information for the correct installation and cabling of the equipment. The general requirements for the integration of PDS are stated in the following subclauses.

9.2.2 Information to be exchanged

The system supplier shall give the necessary documentation for the customer of a PDS to allow the correct installation into a typical system or process. The customer and the system supplier shall agree at an early stage, if special measures have to be taken to achieve compliance with the EMC requirements of the dedicated environment.

The following information shall be made available to the system supplier:

- network impedance and structure (existing capacitor banks, filters, etc.);
- high voltage cable lengths;
- EMC information (actual distortion of the network);
- earthing conditions and specifications;
- information on driven equipment;
- safety requirements according to local regulations, for example colour coding.

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9.3 INTEGRATION OF COMPONENTS WITH VOLTAGES ABOVE 1,000 V

9.3.1 Overview

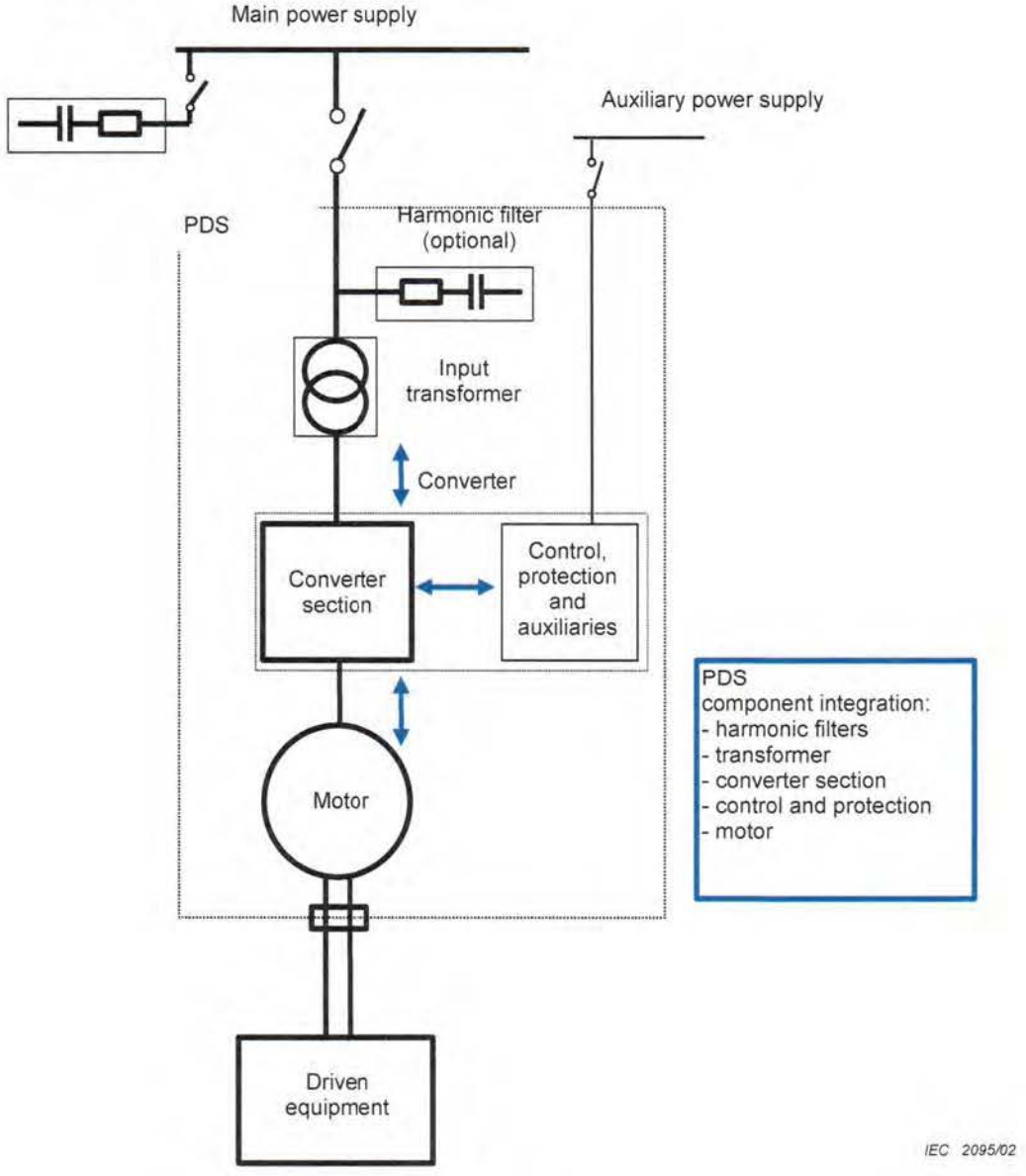


Figure 21 – PDS integration

9.3.2 Transformer integration

Additional overvoltage limitation shall be provided for main power supply transformers, (for example transient energy absorption as lightning arresters (LA)).

The energy of the non-repetitive transients caused by no-load switching of the main transformer feeding the converter assembly is related to the transformer magnetizing energy E. Under the

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assumption of a sinusoidal magnetizing current, the energy stored in the magnetizing impedance of the transformer can be calculated by the equation:

$$E = \frac{i_{mpu}}{4 \times \pi \times f_{LN}} \times S_N$$

where

i_{mpu} is the magnetizing current, referred to the rated transformer current (p.u.);

f_{LN} is the rated frequency (Hz);

S_N is the apparent power of the transformer (VA).

9.3.3 Earthing requirements

(U.S. Difference)

SYSTEM GROUNDING

The application of DC-linked converter systems requires that proper design consideration be given to the system grounding and the voltage ratings of isolation transformers, the motor, and the power converter. An improperly grounded system can result in ground currents circulating between the source and the motor through the power converter. Higher than normal voltage to ground may occur at the terminals of the isolation transformer or the motor. These voltages are caused by common mode voltage generated by the power converter system, which displaces system neutral voltage from ground potential.

The motor terminal-to-ground voltage can be reduced by:

a. Isolating the installation electrical system ground with a transformer.
b. Utilizing separate reactors in both the positive and negative DC link.
c. Connecting the motor neutral to ground through impedance.

If this design practice is properly followed, motor neutral-to-ground voltage can be reduced to near zero. The drive isolation transformer insulation system should be designed for voltage to ground which may exceed rated line-to-line voltage of the secondary winding. Consult the converter equipment supplier for the specific voltage to ground insulation levels required for the motor and isolation transformer.

9.3.3.1 Equipotential bonding of main components

The earthing concept (grounding, earthing, screening) of the drive system should take into account:

- common mode stresses due to the point of earthing of the PDS;
- EMC issues.

The protective bonding circuit and the equipotential bonding (its interconnection) between main components should be considered. Typically it is also necessary to take into account local requirements. The protective bonding concept should be agreed upon between system supplier and customer. It should cover the whole PDS, including:

- the transformer;
- the main converter;
- the motor.

The following items are important examples:

- the material of the protective bonding;

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- the cross-sectional area of the protective bonding;
- the concept of equipotential bonding.

All exposed conductive parts of the PDS shall be connected to the equipotential bonding conductor (protective bonding conductor). Where the protective conductor cannot be easily identified by its shape, position or construction, it shall be clearly identified at accessible positions by the graphical symbol IEC 60417-5019 or by the GREEN-AND-YELLOW bicolor combination.

Each main component is connected to the existing equipotential bonding installed by the customer. Optionally, the equipotential bonding of the main components can be improved by direct interconnections. This has to be agreed upon between system supplier and customer.

The case of power cables is shown in figure 22.

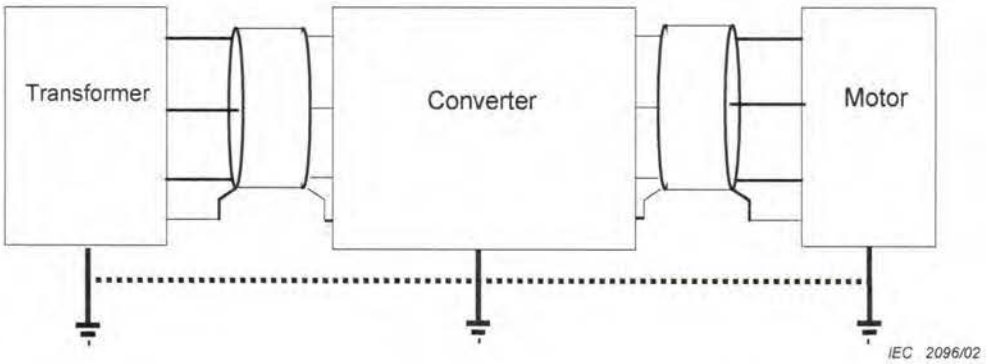


Figure 22 – Example of protective earthing and interconnection of main components

If both ends of the screen are connected to a protective bonding conductor, the thermal loading of the screen by circulating currents (mostly magnetically induced) shall be checked. This aspect is also relevant to safety and EMC (see IEC 61800-3).

9.3.3.2 Earthing of the electrical power part of a PDS

9.3.3.2.1 Earthing

Earthing of the PDS, as a whole system, may be made in different places. The location of the earthing shall be chosen according to the nature of the system: neutral of a common transformer if any, middle point of a common d.c. bus, the star point of any frequency converter output filter or the star point of the motor.

The earthing impedance may be resistive, capacitive or a direct connection. It should be connected to a protective earthing conductor. For EMC reasons, a separate equipotential bonding conductor may be used for connecting the protective bonding conductor of the PDS power part earthing.

The point and the type of earthing, together with the PDS topology (with or without output filter) defines the resulting insulation stress (see 8.2).

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9.3.3.2.2 Fault conditions

It is within the responsibility of the system supplier to specify special requirements in any fault conditions (according to IEC 60204-11) concerning:

- necessary interconnections and their minimum cross-section between main components (due to high currents in fault conditions);
- shield currents of the power cables.

9.3.3.2.3 Leakage currents

They are due to the high frequency harmonic content of the output voltages of the frequency converter, including common mode voltages, and due to the stray capacitance to earth of the cabling system, the windings of the transformer and the windings of the motor. Established and safe earthing practice for the transformer frame, the motor frame and for cables armor or screens should therefore be followed.

9.3.4 Insulation requirements due to converter operation

9.3.4.1 Specific constraints

The voltage stress to earth applied to the different equipment, depends on the PDS power part earthing point.

Special attention is needed in the case of short rise-times and high switching frequencies. In such cases, voltage reflections occur in typical power cable systems. This voltage reflection causes an additional stress to all connected power components.

It is within the responsibility of the system supplier to specify the typical insulation stress, taking into account:

- the PDS power part earthing point and impedance;
- the common mode issues;
- the voltage reflection;
- the fault conditions;
- for the main power parts of the PDS, such as: transformer windings, converter, power cables, motor windings and motor bearings and motor shaft earthing.

9.3.4.2 Transformer windings

Transformer windings are to be defined according to the calculated insulation stresses (peak values, common mode, peak rise time, pulse frequency, reflections) defined by the drive system topology and the PDS power part earthing concept.

These values should be included in the transformer specification made by the PDS system designer.

9.3.4.3 Converter

Converters are to be defined according to the calculated insulation stresses (peak values, common mode, peak rise times, pulse frequency, reflections) defined by the drive system topology and the PDS power part earthing concept.

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Based on the defined voltage stress levels, the requirements in regard to creepages, clearances, impulse tests and a.c. voltage test levels are defined in 9.2.

Reference to IEC 1800-5-1 [U.S. Difference]

9.3.4.4 Power cables

Power cables are to be defined according to the calculated insulation stresses (peak values, common mode, peak rise times, pulse frequency, reflections) defined by the drive system topology and the PDS power part earthing concept.

These values should be included in the power cable specification made by the PDS system designer.

9.3.4.5 Motor windings

(U.S. Difference) SPECIAL MOTOR DESIGNS

Possibilities exist for reducing the heating and spurious torques (produced by harmonics) in adjustable-speed drive supplied motors, by using other than the three-phase stator connections. Harmonic cancellation of the lower harmonics is usually the objective of this effort. Harmonic cancellation may take place in either or both the stator and rotor circuits.

See 8.4.5.

The inverter output filter, if any, and the motor insulation shall be designed in such a way that the motor insulation stress is always within the limits defined in 9.3. (common mode effects included).

9.3.4.6 Shaft voltages and motor bearings

See 8.4.4.1.

In some cases, additional insulation measures are required, such as:

- the complete isolation of the motor shaft is from the motor frame by the insulation of all the motor bearings in combination with a suitable earthing of the shaft to exclude electrostatic charging effects;
- an insulated coupling used to connect the driven equipment.

Filtering can also be considered, according to the topology of the inverter, particularly in the case of PWM voltage source inverters by means of:

- common mode filters;
- dv/dt limitation;
- sinusoidal filter.

The system supplier should give advice, if additional measures are required.

9.3.5 Internal power interface requirements

9.3.5.1 General

The power interfaces of a PDS may be multiple. The different power links such as those between the power transformer and the converter, a d.c. link bus between the input converter

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and the output converter(s) if any, or between the converter and the motor shall be defined for power transmission including the effects of the harmonic content of the current. The design should take into account reflections, possible capacitive coupling, magnetic coupling or radiation.

Cables should preferably be put in parallel by the use of multi-phase cables. Where such appropriate cables are not available, the use of single core cables is possible provided that the multi-phase system is physically constituted for each unit of parallel cables.

9.4 PROTECTION INTERFACE

The PDS should contain the necessary protection functions, system components protection and a generally high system availability. Well-designed protection will protect against contingencies internal and external to the drive system. This should include the protections listed in table 8.

9.4.a POSITIVE BLOCKING (coming from ICS 7, Part 1, Clause 7.3)(U.S. Difference)

For equipment covered in Part 5 and 6, and except for applications in which the operator does not have access to the driven motor, the manually-operated STOP command of the controller or a separate ON and OFF switch shall provide a positive means of blocking rotational power to the motor from the line.

The intent of subclause 7.3 is to minimize the hazards to personnel from an unexpected motion of the motor or driven equipment due to malfunction of a control element or power semiconductor.

9.5 BASIC SYSTEM PROTECTION

The exact requirements for protection of the system depend on the mission and configuration of the drive system. General requirements are defined by NFPA 70. Overload and other overcurrent protection, which generally allow for the safe operation of the equipment, is required by NFPA 70 for motors, capacitor banks, isolation transformers and motor converters. However, to fully protect the equipment from damage caused by other contingencies, additional protection is recommended.

A well-designed system provides protection against contingencies internal and external to the drive system. These may include:

Power source irregularities

1) *Voltage surges*
2) *Over and under voltage*
3) *Phase reversal*
4) *Voltage unbalance*

Overcurrent conditions

1) *Fault currents*
2) *Ground currents*
3) *Internal faults*

Overloads

Equipment overtemperature

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Motor overspeed

Excessive vibration of machine

Lost lubrication of machine

Power converter protection

Power converters are protected by internal solid-state circuits for common faults. Most contingencies will cause the converter to take gate protective action which will force the internal currents and the motor current to zero. This is sufficient as long as the converter components have not failed. In the event of a component failure, the converter should signal the line protective circuit breaker or contactor to trip.

9.6 MOTOR PROTECTION

Motors and motor branch circuits are effectively protected by apparatus in the motor starter or power converter, using relay devices that sequence the converter. Although NFPA 70 requires only overcurrent and overload protection, it is highly recommended that there be means of detecting winding overtemperature, bearing overtemperature, bearing vibration, and differential current in motors rated over 500 horsepower.

Surge protection for motors can be provided by surge arresters and capacitors. The possible effect of the surge capacitor on the converter must be determined to assure satisfactory operation.

Special consideration should be given to protecting induction motors against self-excitation in drives employing large capacitor banks or filters connected between the power converter and the motor. Where the kVAR rating of the capacitor bank exceeds 20 percent to 30 percent of the kVA rating of the motor, it can become self-excited which may result in higher than normal voltage across the motor terminals. Appropriate means should be considered to prevent self-excitation when power is lost. For example, capacitor banks and harmonic filters should be disconnected from motor.

9.7 TRANSFORMER PROTECTION

Isolation transformer protection is typically provided by relays acting through a protective circuit breaker device or to remote alarms. Overcurrent protection in the transformer primary circuit is required by NFPA 70. Ground-fault and differential-current protection are commonly provided on larger units. Care should be taken in selecting relays for this application, taking into consideration adjustable-frequency drive harmonics. Surge protection is typically provided on the primary of isolation transformers. When properly coordinated, such surge protection can protect the entire drive system from line voltage surges caused by lighting and switchgear.

9.7.a HARMONIC FILTERS AND CAPACITOR BANKS

Harmonic filters and capacitor banks require overcurren protection, which is typically provided by fuses. Voltage or current unbalance protection is also commonly provided. See NFPA 70 for further information regarding protection.

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Table 8 – PDS protection functions

Line-side supply	Alarm	Trip	Remark
Outage, phase loss	X	X	
Line overvoltages	X	X	
Line under-voltages	X	X	
Line voltage unbalance	X	X	
Line feeder	**Alarm**	**Trip**	**Remark**
Over-current		X	
Overload	X	X	
Transformer	**Alarm**	**Trip**	**Remark**
Gas relay (Buchholz)	X	X	oil-type only
Over-temperature	X	X	
Loss of cooling media	X	X	
Low oil level	X		oil-type only
Converter	**Alarm**	**Trip**	**Remark**
Overcurrent	X	X	commutation failure, short circuit, etc.
Overload	X	(X)	thermal
Overvoltage	X	X	
Ground fault	X	(X)	
Loss of cooling	X	(X)	
Over-temperature	X	(X)	
Loss of auxiliary supply	X	X	
Loss of communication to process control	X	(X)	
Loss of speed feedback	X		
Motor	**Alarm**	**Trip**	**Remark**
Motor over/under-voltage	X	X	
Motor overcurrent	X	X	
Overload	X	(X)	thermal
Over-speed	X	X	
Winding over-temperature	X	X	
Bearing over-temperature	X	X	
High vibrations	X	X	
Loss of cooling	X	(X)	
Loss of lubrication	X	X	

NOTE 1 Vibration protection functions can be taken care of by the driven equipment supplier.

NOTE 2 (X): conditionally applied.

NOTE 3 The impedance of the supply network at the IPC (see 5.1.1.2), and the input impedances of the PDS (see 8.2.3) shall be considered.

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The demand for and the scope of the PDS protection system increase typically with the power of the drive system. For large or important drives, a diagnostic system to help the customer in fault conditions is recommended.

9.8 DRIVEN EQUIPMENT INTERFACE

9.8.1 Critical speeds

The system supplier, the customer and the driven equipment supplier should come to an agreement on the calculations of the resulting critical lateral speeds of the whole mechanical string and the applicable local requirements (see 8.4.4.3). Special attention should be paid to:

- take into account the influence of the stiffness of the bearing arrangement and the foundation;
- avoid any continuous running with insufficient damping close to lateral critical speeds (±20%).

In the case of active bearings (e.g. magnetic bearings), continuous operation at lateral critical speeds may be possible.

9.8.2 Torsion analysis

Torsional analysis is an important system design tool for PDS and driven equipment to check the torsional stresses in the whole mechanical string, especially, for example in the following operating conditions:

- impact of the harmonic components of the torque in steady state conditions [US Difference]
- start-up;
- 1-phase or 3-phase short-circuit on the terminals of the motor;
- impact of possible commutation failure of the converter;

A torsional analysis is recommended for the PDS and driven equipment, when several of the conditions below exist [U.S. Difference], especially in cases where risk of resonance exists between the inertia of the motor and the inertia of the driven equipment. The most relevant conditions [U.S. Difference] are:

- where the inertia of the driven equipment is higher than the half of the inertia of the motor, actually the risk of high torsion stress grows with increasing inertia of the driven equipment (compared to the inertia of the motor);
- where commutation failures of the converter may cause higher torque dynamics than a three-phase short-circuit of the motor;
- where within the electromagnetic torque (air gap torque) of a motor, any frequency components below 100 Hz can be expected to exceed 1% of the nominal torque in a steady state or during start-up;
- for any drive systems above 5 MVA;
- for a wide speed range (50% for variable torque loads, 30% for constant torque loads) [U.S. Difference]
- for 2 pole motors or speeds greater than 2500rpm [U.S. Difference]
- there is a long shaft connection and/or complex mechanical configurations.

For the torsion analysis, the system supplier shall supply:

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- the air-gap torque pulsations (including the harmonic composition) over the whole speed range;
- the mechanical drawing of the shaft with information on the material properties for the drive side.

For the torsion analysis, the driven equipment supplier shall supply:

- information on any load torque pulsations (including the harmonic composition) over the whole speed range;
- the mechanical drawing of the shaft with information on the material properties.

9.9 PRODUCT MARKING, INSTALLATION, AND MAINTENANCE INFORMATION (U.S. Difference)

9.9.1 Marking and labelling

Converter Nameplate (U.S. Difference)

The following information shall be shown on the converter nameplate:

a. Manufacturer's name

b. Equipment identification

c. Input rating

1. Voltage

2. Maximum continuous current total rms amperes (including harmonics)

3. Frequency

4. Number of phases

5. Maximum allowable AC system symmetical short-circuit current (See application guidelines in Annex A.)

6. Service category

d. Output rating

1. Maximum output voltage

2. Rated continuous current, fundamental rms amperes

3. Overload capacity

4. Frequency range

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5. *Number of phases*

6. *Nominal HP or kW or kVA (optional)*

7. *Phase rotation of output*

9.9.2 Motor Information *(U.S. Difference)*

a. *Motor nameplate as per NEMA standard MG 1*

b. *Maximum operating speed, if different from base speed*

c. *Maximum continuous current over the operating speed range*

d. *Time rating*

e. *Motor rotation at a given input phase rotation*

f. *Insulation system designation*

g. *Maximum ambient temperature*

9.10 INSTRUCTIONAL INFORMATION *(U.S. Difference)*

The following instructional information shall be included with the equipment:

a. *Displacement or total power factor (input) (optional)*

b. *Power converter rating—displacement power factor (output)*

c. *Input harmonic currents and amplitudes*

d. *Output current or voltage harmonics*

e. *Operating modes*

f. *Minimum speed*

g. *Drive system rating—base rating and base frequency*

9.11 WITH CONVERTER ONLY

(U.S. Difference) The following information shall be supplied when the manufacturer provides the converter only:

a. *5.1.1 above*

b. *5.2 except items (f) and (g)*

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c. Maximum output voltage to ground

***9.12 PERMISSIBLE OPERATING SPEED** (U.S. Difference)*

The operating speed range over which the drive system is capable of meeting its steady state torque shall be specified. This operating speed range shall be specified for each of the operating modes for which the drive system is designed.

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Section 10
TESTS

10.1 PERFORMANCE OF TESTS

The performance of tests and test requirements shall be agreed upon in the contractual documents. This subclause specifies the different types of tests. Individual tests of main components, i.e. motors, transformers and converters, shall be performed as specified in the relevant IEC documents. In this standard, the additional test requirements concerning by the drive system, adjustable speed, harmonics, etc. are outlined.

Normally, type tests are required on only one unit. Routine tests shall be performed on all units. If type tests of identical units already exist, the system supplier should provide test *procedure or applicable standards clauses (U.S. Difference)* with the bid.

Special tests such as combined tests, see 3.6.4, and acceptance tests, shall be agreed upon in the contract.

Tests required in order to determine the individual devices and system losses, and hence the efficiencies as defined in clause 11, shall be agreed upon in the contract.

Tests shall normally be performed by the system supplier/*manufacturer (U.S. Difference)* prior to shipment. Other arrangements should be agreed upon prior to order.

Witness tests shall be specified in the order. If not otherwise agreed upon, the system supplier shall notify the customer or his authorized representative at least ten working days prior to all witness tests. The system supplier shall not proceed beyond any witness test without the customer's or his representative's acceptance of the tests or his waiver. The system supplier shall also inform the customer in due time of the other tests as agreed in the contract. The customer will decide whether he or his representative shall be present. The system supplier may anyhow proceed.

Test procedures with the relevant acceptance criteria shall be sent by the system supplier to the customer or his authorized delegate and be accepted by him in due time before the scheduled tests.

10.2 ITEMS OF INDIVIDUAL PDS COMPONENT TESTS

10.2.1 Overview of standard tests for PDS components

Table 9 – Standard tests for PDS components

PDS component	IEC standard
Harmonic filter	IEC 60146-1-3*
Transformer	IEC 60146-1-3 clause 5, IEC 61378-1
Motor	IEC 60034-1, IEC 60034-2
Converter	See table 10
Control and protection	See table 10

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** ANSI/IEEE 18, NEMA CP-1 for harmonic filters, NEMA TR1, UL 1562 for transformers, NEMA MG1 for motors, ANSI/IEEE C57.12 for reactors (US Difference)*

NOTE 1 When the harmonic filter is to be tested under different conditions from those used for its design, tuning conditions, component load and results may be affected.

NOTE 2 If a system full load heat run test is performed in order to determine efficiencies and temperature rises, individual transformer and motor tests for these purposes are not required.

The type test of the filter, if applicable, shall verify that the performance parameters of the filter are met. This test should also, if it is practical to do so, verify that the design criteria with respect to maximum voltages and current stresses, as well as temperature levels are fulfilled.

NOTE 3 Additional commissioning tests are normally required.

NOTE 4 The filter can be a common plant filter.

If applicable, it is desirable that equipment temperature rise should be determined by a full load heat run test which includes the real harmonics current and voltage distortion, see 10.3.

If the type test of the transformer is based on the separate loss method according to IEC 60076 or IEC 60726, which only takes into account the fundamental sinusoidal component, adequate margins for losses and temperature rise due to the real harmonic components shall be documented. These losses and associated temperature margins shall be theoretically calculated in advance of the tests.

All tests specified in IEC 60076 and IEC 60726 shall also apply to converter transformers, if not in contradiction with the tests specified in the above clause.

The above defined losses and temperatures shall be calculated based on rated fundamental current and maximum harmonics current distortion.

The tests specified in clause 5 of IEC 60146-1-3 are to be regarded as special tests applicable to the transformer.

A separate test of the motor, according to IEC 60034 does not guarantee the intended operation of the PDS and driven equipment. Ripple and harmonic content shall be considered either by testing the motor supplied with a converter of similar characteristics to those of the converter with which it will be supplied (see combined test), or by providing information. In that case, the system supplier should provide information on how to take into account all relevant phenomena, for example:

air gap pulsating torque components and rotor inertia, required for torsion analysis;

- additional losses for efficiency determination;
- total temperature rise;
- additional acoustic noise.

NOTE 5 If the motor has two 3-phase windings with a 30° phase shift, the equivalent test voltage and test current should be found.

Based on the drive system's load envelope, the temperature rise of the motor shall be determined at minimum and at rated speed, at base speed if the drive system has a constant power range, and at maximum speed if it is different from the rated speed. Based on the results of these measurements, it shall be decided whether further measurements, due to cooling system (clearing of losses) and/or modulation method are required (production of losses).

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10.2.2 Standard tests of the converter and control

10.2.2.1 Overview

Table 10 – Standard tests of the converter as component

Test	Type test	Routine test	Special test	Specification and subclause
Insulation (see note 1)	X	X		4.2.1 of IEC 60146-1-1
Light load and operation (see note 2)	X	X		4.2.2 of IEC 60146-1-1 7.3.5 of IEC 60146-2
Rated current/output	X			4.2.3 of IEC 60146-1-1 7.3.6 of IEC 60146-2
Overcurrent capability (see note 3)			X	4.2.12 of IEC 60146-1-1 7.3.7 of IEC 60146-2
Current sharing	X			10.2.2.3
Voltage division	X			10.2.2.3
Interphase ripple voltage and ripple current			X	4.2.15 of IEC 60146-1-1
Power loss determination (see annex C)	X			4.2.4 of IEC 60146-1-1 7.3.9 of IEC 60146-2
Temperature rise (see note 4)	X			4.2.5 of IEC 60146-1-1
Measurement of inherent voltage regulation			X	4.2.8 of IEC 60146-1-1
Checking of auxiliary devices	X	X		4.2.7 of IEC 60146-1-1
Checking the properties of the control equipment	X	X		See 10.2.2.2 and note 2
Checking the protective devices	X	X		4.2.10 of IEC 60146-1-1
Audible noise (commissioning test)			X	4.2.14 of IEC 60146-1-1
Power factor			X	
Additional tests			X	4.2.16 of IEC 60146-1-1

NOTE 1 Insulation tests may be done with the power semiconductor devices short-circuited. The manufacturer of the component should have separately checked the insulation level of these devices.

NOTE 2 A light load test might be performed with a motor of smaller power than the assigned one. However the voltage and speed/frequency ranges should be relevant.

NOTE 3 The overcurrent of the converter reflects the overload capability of the PDS [6.1.4]. Specified values of short time over current or starting up sequences of actual load should be applied for the time interval specified.

NOTE 4 The temperature tests should verify adequate margins for the power semiconductors as well as other critical devices, for example capacitors and printed wiring boards (PWB). To document semiconductor margins, the converter manufacturer should prior to the tests produce theoretical calculations of the junction temperature.

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10.2.2.2 Insulation – Functional – Control

The insulation tests of the converter shall take into account the maximum transient and stationary voltage spikes.

The functional test shall consist of at least the following:

starting and acceleration to minimum operating speed, according to the load window;

- stable operation at a reasonable number of speed settings, if possible including the rated speed and the maximum speed, if different from the rated value;
- stable acceleration and deceleration between the above-mentioned operating speeds.

NOTE For the purpose of testing, some additional inertia might be appropriate.

Rated current and overcurrent tests shall either be performed as part of the system tests, see 10.3, or as a special device test where the relevant equipment for loading the converter is at hand.

Routine testing of the control functions/equipment can be done with a smaller test motor and adequate scaling of the measuring devices. The light load test (see 10.3.3.1 or table 10), also checks some of the control functions. By adequate scaling, the current limit function might be tested, as well as acceleration and deceleration, if relevant.

Type testing of the control equipment can be done using a motor with a lower rating.

10.2.2.3 Protections and specific items

Routine testing of the protection functions/equipment can be done by simulating the failure causes by operating the relevant switches.

For the type testing of the protection functions, the system supplier shall propose an appropriate test program.

Current sharing – If parallel connected power semiconductors and/or converters are used in the drive system, the current sharing should be checked. This test shall be performed at rated output current.

Actual cases are:

- input rectifier and/or inverter in 12-pulse configuration;
- motor stator with two parallel windings (in 6-phase configuration).

The balance shall be adequate to ensure that no device is stressed beyond design values under the worst case conditions (derived from component tolerances, design margins, service conditions, etc.). These design limits shall be identified before the tests start.

Voltage division – If two or more power semiconductors and/or converters are connected in series, voltage division shall be checked. The voltage division shall be adequate to ensure that no device is stressed beyond design values under the worst case conditions (derived from component tolerances, design margins, service conditions, etc.). These design limits shall be identified before the tests start.

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10.3 DRIVE SYSTEM TESTS

10.3.1 General

10.3.1.1 The tests should be done preferable on rated motor load. Question of whether these test should be done at manufacturer or customer site due to voltage and load considerations.

Unless otherwise specified in the reference standard of table 11, drive system tests are special tests and shall be contractually agreed upon. If performed, some of them will replace tests described in 10.2.

A load is required: either the driven equipment, a calibrated load or an another specific load equipment. If efficiency measurements are to be performed, this load machine has to be calibrated. If two drive systems are available, the back-to-back method can be applied. See clause 11 for the determination of efficiencies.

The items for the PDS tests are given in table 11 below.

Table 11 – Drive system tests

Steady state performance	Reference standard or specification subclause
Light load test	10.3.3.1
Load characteristic test (Load envelope test)	10. 3.3.2
Load duty test (Intermittent load test)	10. 3.3.3
Allowable full load current versus speed test	10. 3.3.4
Temperature rise tests	10. 3.3.5
Efficiency	10. 3.3.6 and clause 11
Line-side current distortion content	10. 3.3.7
Power factor	10. 3.3.8
Checking of auxiliary devices	10. 3.3.9
Checking co-ordination of protective devices	10. 3.3.10
Checking properties under unusual service conditions	10. 3.3.11
Shaft current/bearing insulation	10. 3.3.12
Audible noise	10. 3.3.13
Torque pulsation	10. 3.3.14
Motor vibration	10. 3.3.15
EMC tests	10. 3.3.16 and IEC 61800-3
Dynamic performance	10.3.4
Current limit and current loop test	10.3.4.1
Speed loop test	10.3.4.2
Automatic restart/re-acceleration	10.3.4.3

10.3.2 Test set-up

See figure 23 for the measuring circuit. In this figure, physical variables are directly measured, or calculated from measurements:

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- U for voltage;
- I for current;
- N for speed;
- M for torque;
- θ for temperature;
- P for active power, etc.

Additional measurements could be vibrations, acoustics and signal interference.

NOTE If efficiencies are to be determined, great care should be taken in choosing the instruments. The instruments should measure true r.m.s. with sufficient bandwidth to include harmonics up to 40th, and a sufficient accuracy to allow the losses to be determined within 10 %. Refer also to clause 11.

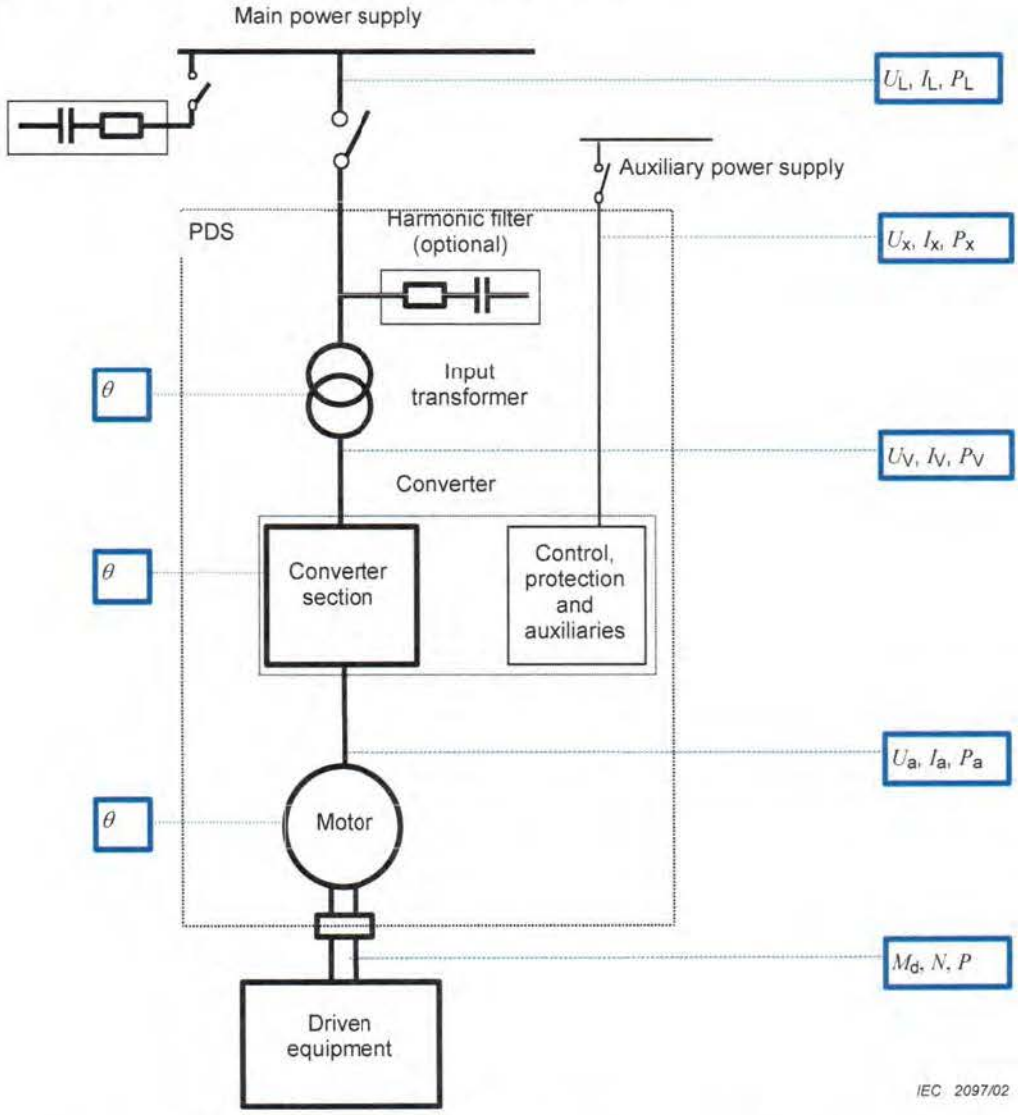


Figure 23 – Reference measuring points for drive system tests

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10.3.3 Steady state performance tests

10.3.3.1 *(US Difference) The tests should be done preferable on rated motor load. Question of whether these test should be done at manufacturer or customer site due to voltage and load considerations.*

10.3.3.2 Light load test

The shaft of the motor is coupled to a load that is able to provide conditions to the drive under test so that the control system can be proven. If agreed upon between the system supplier and the customer, a no load test can be used.

NOTE The load is the driven equipment or, for test purposes, a simulation of the driven equipment.

10.3.3.3 Load characteristic test

Measurements shall at least be performed at the minimum speed and at the rated speed on the upper torque line of the load window, and at the maximum speed and the maximum torque if not identical to the rated values. The following data are measured:

- voltage U_L, current I_L and power P_L at the transformer input;
- voltage U_V, current I_V and power P_V at the converter input;
- voltage U_a, current I_a and power P_a at the motor input;
- temperature rise of each main component.

NOTE 1 The system supplier and customer have to agree where to perform this test, in the workshop, during commissioning or at another test site.

NOTE 2 If this test is also to be used for loss and efficiency calculation, reference is given in clause 11 for the calculations and instrumentation. If not, instruments with adequate accuracy for the fundamental sine wave are sufficient.

NOTE 3 The load could be the driven equipment, a load machine or an identical drive in back-to-back configuration.

10.3.3.4 Load duty test

This test is only relevant if the customer defines an intermittent load duty cycle.

The motor shall be coupled to a load that is capable of providing the defined load duty profile over a long term run, to verify that the temperature rise of all equipment reaches stable conditions within ratings.

10.3.3.5 Allowable full load current versus speed

This test shall establish the current, and hence torque margins if any, above the defined load window. The test is based on the system supplier's theoretical calculations, and shall verify that temperature rises under the given cooling conditions are still within agreed limits.

10.3.3.6 Temperature rise tests

The temperature rise tests are part of the load characteristic test, see 10.3.3.2. The temperature rise tests are to be continued until all temperatures are stabilized.

10.3.3.7 Efficiency

See 6.1.3 and clause 11.

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10.3.3.8 Line-side current distortion content

This measurement is performed using instrumentation and techniques in accordance with IEC 61000-4-7 and *IEEE 519 (US Difference),* preferably under rated operating conditions. Harmonics up to at least the *50th (US Difference)* harmonic should be measured.

The short-circuit conditions at the PC during the test should be known and identified in the test protocol.

If a specific filter is designed for the drive, it should be connected during the test.Power factor

The poer factor measurement shall be made as part of the load characteristic test, see 10.3.3.2.

10.3.3.9 Checking of auxiliary devices

The function of all auxiliary devices that are not completely tested *or certified* (US Difference) shall be checked. Examples of such devices are: motor fans, lubricating oil, external circuit breakers, disconnect switches, etc.

NOTE If convenient this can be done while performing the light load test, see 10.3.3.1.

10.3.3.10 Checking co-ordination of protective devices

The checking of these devices shall be done, as far as possible, without stressing the components of the equipment above their rated value. Reduced settings are recommended in order to obtain reduced stresses.

Due to the wide variety of protective devices, the details should be worked out in the test procedure to be followed. The following should be included as a minimum:

a) verification of the emergency stop function, if applicable;
b) test/simulation of all alarm and tripping functions, especially
   - over-speed,
   - overvoltage,
   - overload;
c) loss of speed feedback;
d) earth fault;
e) test of current/torque limiting functions.

10.3.3.11 Checking properties under unusual service conditions

Unusual service conditions are mainly environmental conditions, such as temperature, humidity, salty air, altitude, etc. beyond IEC standard specifications for the relevant equipment.

Such conditions might require special design or rating criteria or extra protective coating, etc. and shall be specified by the customer in his request. Corrective measures and test criteria shall contractually be agreed upon.

10.3.3.12 Shaft current/bearing insulation

Shaft currents may result due to common mode effects and harmonics in the motor voltage and current. While these currents are small in magnitude, they may cause damage to either anti-

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friction or sleeve bearings. Testing methods for their presence should be agreed upon by the system supplier and the customer.

10.3.3.12 Audible noise

The tests shall be performed in accordance with ISO 1680 and IEC 60034-9. [US Difference]

NOTE Low audible levels might require an outer sound suppression hood.

Note 2 Where the audible noise is likely to exceed 85 dbA, limiting the exposure of testing or operating personnel should be addressed. [US Difference]

10.3.3.13 Torque pulsation

Relative levels of air gap torque pulsation may be measured under no load conditions using speed and/or current measurements, providing that adequately sensitive and dynamic measuring devices are at hand. Ideally, air gap torque pulsation arising within a specific PDS should be measured with known load inertia, proper load and PDS mechanical coupling with a shaft mounted torque sensing equipment. Then it is possible to calculate the air gap torque pulsations.

10.3.3.14 Motor vibrations

The vibration tests shall be performed in accordance with IEC 60034-14 and at the same load points as the load characteristic test, see 10.3.3.2.

10.3.3.15 EMC tests

EMC tests are defined in IEC 61800-3.

10.3.4 Dynamic performance tests

10.3.4.1 Current limit and current loop

These tests characterize the dynamic performance of the converter or the drive independently of the driven equipment.

An incremental load change or speed reference step is provided to require the converter to reach its pre-set current limit point. The rise time of the current, the overshoot magnitude, duration, and damping characteristics can be analyzed as required.

Loop bandwidth and harmonic analysis, can be used to establish the response between current reference and current measurement (feedback).

These tests should be performed at the same speed points as the load characteristics test, see 10.3.3.2.

10.3.4.2 Speed loop

A step in speed reference at no load or light load will be provided and correctly selected to measure the speed response. The step should not activate the current limit.

A small load step may be provided in order to measure the speed response versus the load. The step should not activate the current limit.

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These tests should be performed at the same speed points as the load characteristics test, see 10.3.3.2.

10.3.4.3 Automatic restart – re-acceleration

These functions shall be checked if specified by the customer.

10.3.5 Back-to-back test

The back-to-back test requires a second PDS of appropriate characteristics. In the back-to-back test, one PDS operates as motor, and the other operates as generator. Figure 24 shows the test scheme of the back-to-back test.

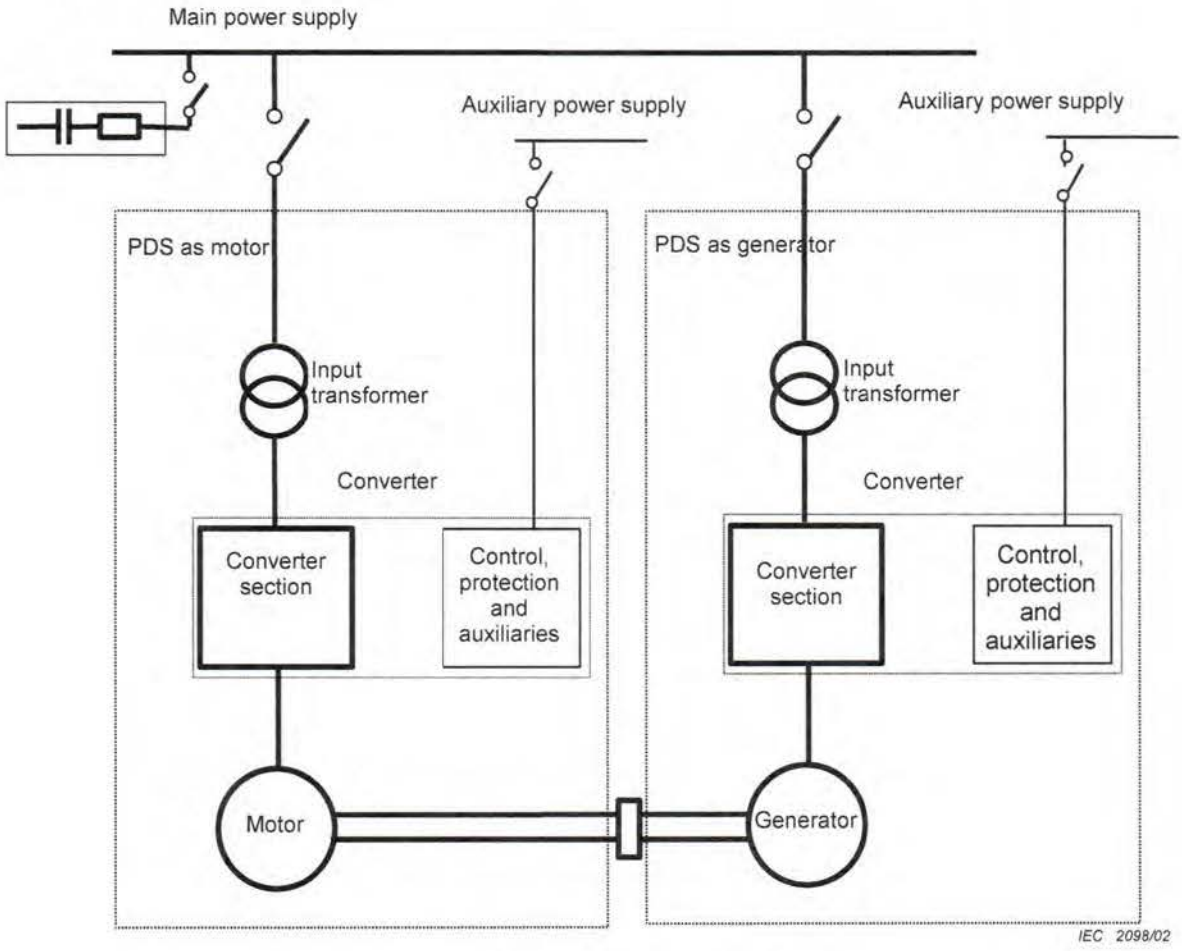


Figure 24 – Back-to-back test

10.3.6 Zero power factor test

Based on agreement between the system supplier and the customer, a zero power factor test can be performed for current source converters instead of actual drive system tests.

A zero power factor test means that the converter supplies the rated or overload current to the synchronous motor under test at the condition of zero power factor without mechanical load.

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In this case, the converter rated current test, the overload capability test, the temperature rise test, the power loss determination, the checking of the properties of the control equipment and the checking of the protective devices, can be performed in an appropriate practical test.

10.3.7 Short-Circuit Tests (from ICS 7, Part 7) (U.S. deviation)

Short-Circuit Withstand Capability

The converter shall meet the test requirements of UL 347A and UL 508C (or UL 61800-4), as modified by the following test procedure and compliance criteria, as to short-circuit withstand capability ratings expressed in terms of available rms symmetrical amperes, rated system voltage and the type and ratings of short-circuit protective device(s) stated by the manufacturer.

10.3.7.1 Test Procedure

The input power supply must be calibrated to be capable of supplying fault current equal to or greater than the maximum allowable AC system symmetrical short circuit rating of the converter. The configuration of the input power supply must be corner-grounded delta or line grounded wye.

Surgical cotton balls are placed in all the enclosure ventilation holes. A 3 ampere, 5,000 volt fuse is connected between the ungrounded enclosure and ground. The specified branch-circuit protection fuses or switchgear are installed ahead of the converter, if not provided as an integral part of the converter.

The output of the converter is shorted line-to-line with all the electrical protective circuits active and the converter operating at its maximum frequency and voltage output. A small motor shall be permitted to be used on the output of the converter, if required for normal operation.

10.3.7.2 Test Compliance Criteria

The equipment passes the test if the fuse connected from the enclosure to ground does not open (no striking of an arc to the enclosure), there is no ignition of the cotton placed around the openings in the converter enclosure, and no other manifestation of a fire hazard occurs.

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Section 11
EFFICIENCY DETERMINATION

11.1 GENERAL

Two approaches can be taken to determine the total drive efficiency: the segregated loss method and the system full load test. With the first approach, the losses of the individual system components are determined separately as the sum of the individual losses, assuming ideal fundamental sinusoidal waveforms, as specified in the relevant IEC standards (see table 9), plus the additional losses due to non-sinusoidal voltage and current waveforms. Total drive system losses are the sum of all individual component losses.

The second approach allows the determination of the true losses of the system, which is configured to work in its intended operating conditions. Two categories of methods are applicable to follow this approach.

a) The determination of losses by direct measurement of the input and the output power. This method requires highly accurate measurements of the power in the input and the output sections of the system (or of each of its components, if required), output power can be measured by means of a calibrated load machine (see 11.3).
b) The direct measurement of losses. This measurement can be accomplished essentially by using a back-to-back configuration if applicable (see 10.3.5) or by means of the calorimetric method.

By directly measuring the losses, method b) gives more accurate results, and is preferable in the case of systems characterized by high efficiency values.

The system supplier and customer shall agree in the contract and order which method to use and the load points to be measured.

The general efficiency formula both for individual system components and the complete drive system is:

$$\text{Efficiency } (\eta)\ \% = \frac{\text{output power } (P_{out})}{\text{input power } (P_{in})} \times 100$$

$$\text{Efficiency } (\eta)\ \% = \frac{\left[\text{input power } - \text{ losses}\right] (P_{in} - P_{loss})}{\text{input power } (P_{in})} \times 100$$

$$\text{Efficiency } (\eta)\ \% = \frac{\text{output power } (P_{out})}{\left[\text{output power } + \text{ losses}\right] (P_{out} + P_{loss})} \times 100$$

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A choice between these three formulae is determined by the available measuring points. A generally higher accuracy is achieved by determining the individual losses based on the use of the second or third formula. In this case, the cable losses are normally neglected because they are often not under the system supplier's control.

NOTE Great care should be taken in choosing the instruments. The instruments should measure true r.m.s. with sufficient bandwidth to include harmonics up to 40th, and a sufficient accuracy to allow the losses to be determined within a 7% total tolerance (see 6.1.4), and respectively 10% for each main component.

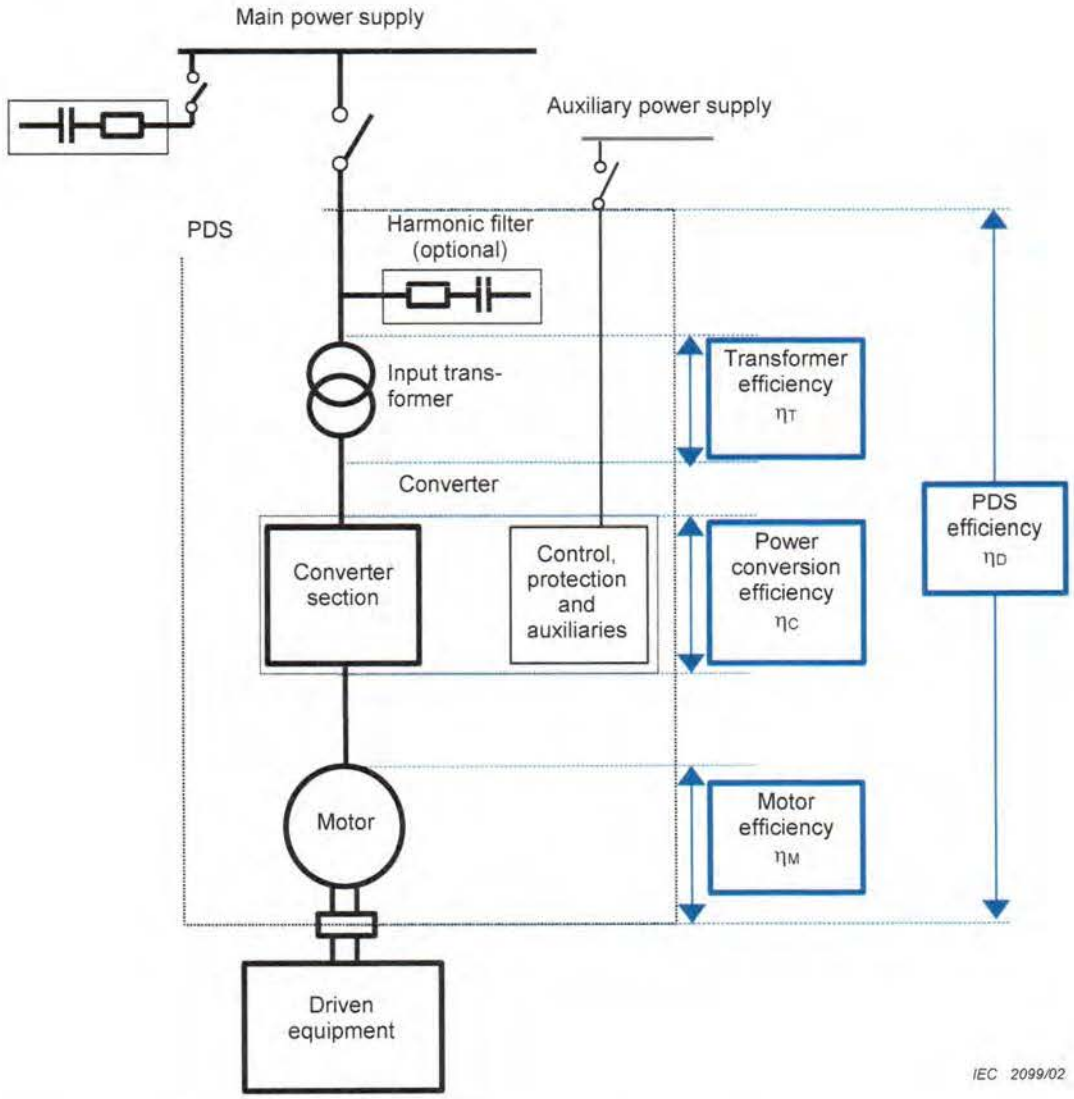


Figure 25 – PDS hardware configuration and individual component efficiency

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The definition of the individual PDS component efficiency is as follows:

– transformer efficiency	from the point of coupling to the converter input terminals, see 11.2.2.
– power conversion efficiency	see 3.1.6
– motor efficiency	from electrical input terminals to mechanical output, see 11.2.4.
– PDS efficiency	see 3.1.5

11.2 SEGREGATED LOSS METHOD

11.2.1 General

The relevant IEC standards for the individual components of the drive system, transformers, reactors, motors and converters shall be used. In addition, the manufacturers shall calculate the additional losses due to the non-sinusoidal voltage and/or current shape. These methods should be verified by measurements on individual components of similar design and ratings.

For cases where due to design, time, or other reasons verified calculation methods are not available, the following subclauses present empiric formulas for the additional harmonic losses. The additional losses caused by harmonic currents and voltages are then given as fixed multipliers of the fundamental losses. These multipliers shall only be used if more reliable data is not at hand.

NOTE The losses determined by this method should as fall-back be used for efficiency calculations only, and should not be used to determine temperature rises.

11.2.2 Transformer losses

Special requirements for converter transformers are treated in IEC 60146-1-3 and IEC 61378-1. These standards refer to IEC 60076 and IEC 60726 for general liquid cooled and direct air cooled transformers respectively. Fundamental iron and copper losses as well as the relevant stray losses and auxiliary losses shall be determined according to these standards.

Unless otherwise agreed, the determination of harmonic losses should be based on the following assumptions regarding the input transformers feeding diode or thyristor bridges. The transformer voltage distortion is small compared to the current distortion. The additional losses therefore occur mainly in the windings, and are heavily dependent on the design of these windings. The additional harmonic losses $P_{h,1}$ shall be calculated as:

$$P_{h,1} = k_1 \times P_{Cu,1}$$

where

k_1 = 0,3 if the winding current is 6-pulse or lower, or

k_1 = 0,2 if the resulting winding current is 12-pulse or higher;

P_{Cu} represents transformer winding copper losses fundamental component.

This factor also includes additional stray losses. The values can be substantially lower for an optimized design of the transformer. The total transformer losses P_{total} are:

$$P_{total} = P_1 + P_{h,1} + P_x$$

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where

P_1 represents the fundamental losses according to IEC 60146-1-3

P_x are auxiliary losses, if any.

11.2.3 Power converter

11.2.3.1 General

The converter normally consists of an input 6- or 12-pulse line commutated rectifier, an inter-stage filter consisting of reactors and/or capacitors and an output inverter. The inverter is either of the current source load commutated type, or the voltage source pulse width modulated type.

Converter losses generally comprise:

- semiconductor conducting losses (see annex C);
- semiconductor switching losses(see annex C);
- protective devices (snubber) losses (see annex C);
- converter filters;
- auxiliary losses;
- power supplies for control and protection devices etc.;
- fans and/or pumps for the cooling medium.

The components and the determination of losses are described in IEC 60146-1-1 and IEC 60146-1-2, and additionally see annex C for specific power semiconductor and snubber loss calculation.

Equipment causing auxiliary losses may be common to both rectifier and inverter parts.

11.2.3.2 Rectifier

The losses shall be determined at rated (base) load and rated (base) firing angle, and at maximum load and associated firing angle, if different.

11.2.4 Inverter

If the inverter is load commutated, the losses are mainly the same as for the rectifier, and the item is covered by IEC 60146-1-1 and IEC 60146-1-2. The losses shall be determined at the rated (base) load and the rated (base) firing angle, and at the maximum load and associated firing angle, if these are different.

Self-commutated inverters are covered by IEC 60146-2.

The losses shall be determined at the rated (base) load and at the maximum load, if different, both with the correct associated PWM pattern.

11.2.4.1 DC link reactor

Specifications for reactors are found in IEC 60146-1-3.

Losses including harmonic components should be calculated based on verified methods. If such methods are not available, the factors below can be used as fall-back.

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Based on the rated d.c. link direct current, the additional losses caused by the ripple current shall be calculated as follows:

$$P_{h,2} = k_2 \times I^2 R_{d.c.}$$

with

k_2 = 0,10 for air cores;

k_2 = 0,15 for iron cores;

$R_{d.c.}$ representing the resistance corresponding to copper losses for d.c. current.

This formula is applicable for reactors in CSI and for reactors in VSI.

11.2.4.2 DC link capacitor

Capacitor losses are normally negligible.

11.2.4.3 Other losses

Other losses due to auxiliary circuits, protective devices, cooling etc. shall be included separately.

11.2.5 Motor losses

11.2.5.1 General

Two alternative segregated test methods exist in accordance with IEC 60034-2:

- driving the motor to be tested by a calibrated motor;
- connecting the motor to an adjustable sinusoidal voltage source.

The first alternative is normally most convenient for synchronous motors and the second most convenient for induction motors. However, if only the voltage is adjustable, and not the frequency, it is only possible to determine the efficiency at one speed, given by the supply frequency.

Both alternatives make it possible to determine the following individual loss components:

- friction and ventilation losses;
- core losses;
- stator winding losses (I^2_R losses);
- rotor losses.

Excitation losses and auxiliary losses such as lubrication oil pumps and independent ventilators, as relevant, shall also be included by measurements.

11.2.5.2 Single winding motors

The methods for determining the efficiency of motors operating with pure sinusoidal voltages and currents are given in IEC 60034-2. In addition, provisional methods for taking into account harmonic losses are included in annex A of IEC 60034-2.

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11.2.5.3 Dual winding motors

If the phase shift between the three-phase-windings is zero, the windings can be connected in parallel for testing, and both alternatives are possible.

If the three-phase systems have a mutual phase shift, and if both ends of the windings are not available for a series connection of the windings, the only means of testing is driving the motor by a calibrated motor, because adjustable power sources with a phase shift are unlikely to be available.

During the short-circuit measurements, the two three-phase windings should be shorted independently.

11.2.5.4 Harmonic losses

Unless otherwise agreed the determination of harmonic losses should be based on the following assumptions. In a similar manner as for transformers, the additional harmonic losses occur mainly in the windings (the stator and the rotor windings of the motor).

If the shape of the current is a quasi-square wave, the additional harmonic losses $P_{h,3}$ should be estimated as:

$$P_{h,3} = m \times k_3 \times I_1^2 \times R_{M,1}$$

with

m as the number of phases;

k_3 = 0,15 for three-phase winding;

k_3 = 0,10 for six-phase winding.

With respect to induction motors fed from voltage source converters, the situation is far more complex, depending on modulation method, pulse pattern and motor design, especially the rotor cage. As a fall-back, the following factors should be used:

k_3 = 0,10 for sinusoidal PWM in a range up to 80% of the rated speed or for three-level PWM converters;

k_3 = 0,20 for PWM above 80% of the rated speed and at least six pulses per fundamental period;

k_3 = 0,30 at high speed without PWM, i.e. in a six-step operation.

Application of the formula giving $P_{h,3}$ is only valid for the rated current (I_{N1}), because the current harmonic content is rather independent of the load for voltage source converters.

In the above equation $R_{M,1}$ is the resulting stator ($R_{S,1}$) and rotor resistance ($R_{R,1}$), for one phase, referred to the stator winding, at the fundamental frequency.

$$R_{M,1} = R_{S,1} + R_{R,1}$$

The assigned factors k_3 take into account additional harmonics and stray load losses.

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The rotor phase resistance referred to the stator side should be determined by measuring the short-circuit losses at the rated current and the locked rotor. For a m-phase induction motor, stator losses are calculated as follows:

$$R_R = \frac{\left(P_{SC} - mI_N^2 R_S\right)}{mI_N^2}$$

where

I_N is the rated stator current.

11.3 FULL LOAD SYSTEM TEST

11.3.1 General

Following principles, this is the only way to obtain the real losses of the system and hence the efficiency. It is also the only way to measure the real temperature rises of the individual devices before commissioning.

The method requires a load machine of at least the same power as the drive motor. Shaft power has to be measured either by speed and torque on the shaft, or the load machine has to be calibrated. If two identical regenerative drive units are available, the back-to-back test set-up should be used.

The measuring set-up, symbols and indexes, are shown in figure 23. The main power circuit losses for the individual devices can principally be measured directly by the difference between input and output power:

$$P_{loss} = \sum \left(P_{in} - P_{out}\right) = \left(P_L - P_V\right) + \left(P_V - P_a\right) + \left(P_a - P_s\right) + P_x$$

Due to the high efficiencies involved, the resulting losses constitute a relatively small difference between two relatively big figures. Therefore, the second formulation of the above formula, which indicates individual measurement of each main component, gives a higher accuracy. The accuracy of the instruments should also be very high, typically 0,02 % or better, with a bandwidth of up to the 40th harmonic. Additional information is given in IEC 60034-2 amendment 2.

11.3.2 Transformer losses

The transformer losses consist, besides the losses measured directly, of auxiliary losses such as fans or pumps for forced cooling, if relevant. Other auxiliary losses, for example stray losses in the structure and outer hood are already included in P_L.

The transformer efficiency is:

$$\eta_T = \frac{P_V}{P_L + P_{Aux,\,1}}$$

Filter losses should, if relevant, be measured individually, and should not be part of the transformer losses.

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11.3.3 Converter losses

Auxiliary losses not included in the direct measurements might be:

- cooling fans and pumps as relevant;
- external power supplies.

The resulting converter efficiency is:

$$\eta_C = \frac{P_a}{P_V + P_{Aux,2}}$$

11.3.4 Motor losses

Auxiliary losses not included in the direct measurements might be:

- externally powered cooling fans;
- externally powered pumps for a secondary cooling medium;
- exciter system power;
- external lubricating oil pumps.

NOTE Only pump and pump motor losses and external transport losses are to be considered. The rest of the pump work is included in the main motor bearing losses.

If the back-to-back method is used, the shaft power P_S is not directly known by measurements. The two identical machines, one operating as a motor and the other as a generator, shall be adjusted as close to the same, normally rated, voltage, current and power factor values as possible. The mean values between the two machines shall be regarded as the measurement parameter. Half of the losses, given as the difference between motor input power P_a and generator output power P'_a, shall be regarded as the drive motor main losses:

$$P_{loss,3} = \frac{1}{2} \cdot \left(P_a - P'_a\right)$$

The motor efficiency is:

$$\eta_M = \frac{P_S}{P_a + P_{Aux,3}} = \frac{P_a - P_{loss,3}}{P_a + P_{Aux,3}}$$

11.3.5 Harmonic filter

If the harmonic filter is an integral part of the drive, either coupled on the secondary side of the transformer or through a separate winding, the filter losses will be measured as part of the transformer losses. They might be separated by individual measurements.

If the filter is placed somewhere on the primary side of the transformer, an individual measurement is required to verify the filter losses.

11.3.6 Total drive system efficiency

The total drive system efficiency is:

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$$\eta_{drive} = \frac{P_S}{P_L + \sum P_{Aux}} = \frac{P_a - P_{loss,3}}{P_L + \sum P_{Aux}}$$

NOTE 1 The description of the full load direct method is based on electrical measurements only. If some of these measurements are exchanged with calorimetric measurements, one will have to take into account also minor heat transfers, such as radiated and conducted heat from the machine frame to ambient, etc.

NOTE 2 When planning and preparing protocols for the above measurements, make sure that all auxiliary losses are included, but only once.

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Annex A
MOST COMMONLY USED DRIVE SYSTEM TOPOLOGIES
(informative)

A.1 OBJECT

The purpose of this annex is to show the simplified block diagrams of the most used drive system topologies. Clause 4 should be referred to for general information. Optional devices may be added such as different filters, transformers, regenerative units, etc.

The simplified block diagrams use the symbol of a switch for semiconductor switches that can be turned off by its control signal. Note that if there is no diode symbol in parallel of the switch symbol, the semiconductor switch should have reverse blocking capability.

A.2 DRIVE SYSTEM TOPOLOGIES WITH INDIRECT CONVERTERS

A.2.1 Load commutated inverter (LCI) drive systems with a synchronous motor

The basic structure of the drive is shown in figure A.1.

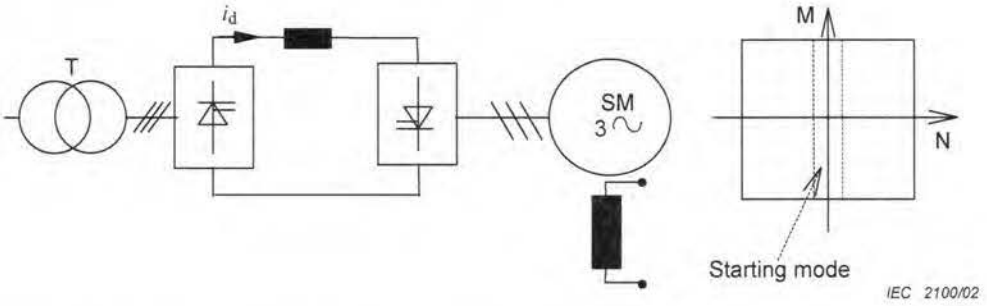


Figure A.1 – Basic structure of an LCI synchronous motor drive system

This drive essentially consists of:

- a line commutated line-side converter;
- a load commutated motor-side converter;
- a d.c. reactor in the d.c. link;
- a synchronous motor;
- an excitation system, supplying the motor field.

The general characteristics of the drive are:

- a four-quadrant operation;
- a pulsating torque below a minimum speed (in starting mode);
- a low line-side power factor, depending on input power.

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A.2.2 LOAD COMMUTATED INVERTER DRIVE SYSTEMS WITH AN INDUCTION MOTOR

The basic structure of the drive is shown in figure A.2.

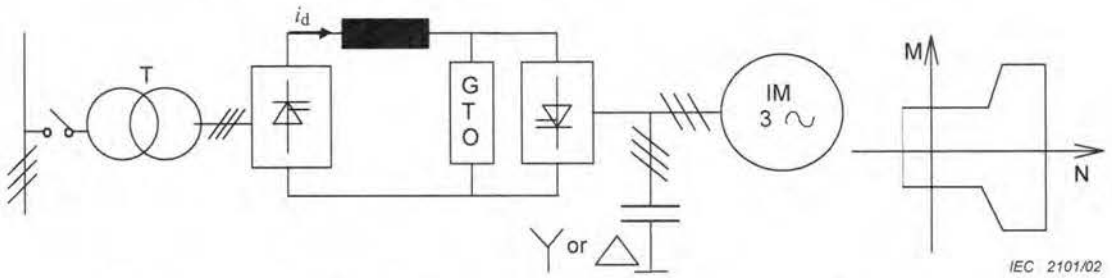


Figure A.2 – Basic structure of an LCI induction motor drive system

This drive essentially consists of:

- a line commutated line-side converter;
- an externally commutated motor-side converter;
- a d.c. reactor;
- a common turn off device (GTO);
- an output capacitor bank;
- an induction motor.

The general characteristics of the drive are:

- a two quadrant operation;
- a reduced motor torque ripple with a proper output filter;
- a low line-side power factor, depending on input power.

A.2.3 CURRENT SOURCE INVERTER (CSI) DRIVE SYSTEMS WITH AN INDUCTION MOTOR

The basic structure of the drive is shown in figure A.3.

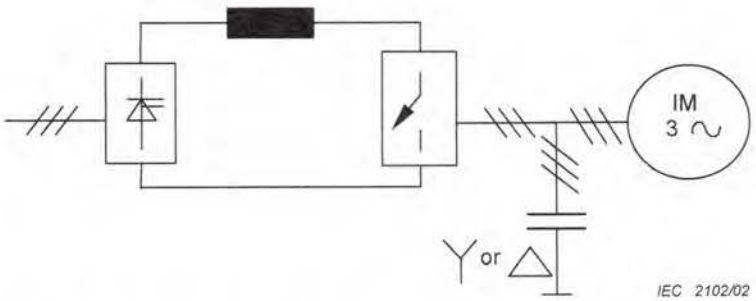


Figure A.3 – Basic structure of a self-commutated PWM-CSI inverter for an induction motor drive system

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This drive essentially consists of:

- a line commutated line-side converter;
- a self-commutated motor-side converter;
- a d.c. link reactor;
- an output capacitor bank;
- an induction motor.

The general characteristics of the drive are:

- a four quadrant operation;
- a low motor torque ripple (negligible if the PWM technique is adopted);
- a low line-side power factor, depending on input power.

A.2.4 DUAL CURRENT SOURCE INVERTER (CSI) DRIVE SYSTEMS WITH AN INDUCTION MOTOR

The basic structure of the drive is shown in figure A.4.

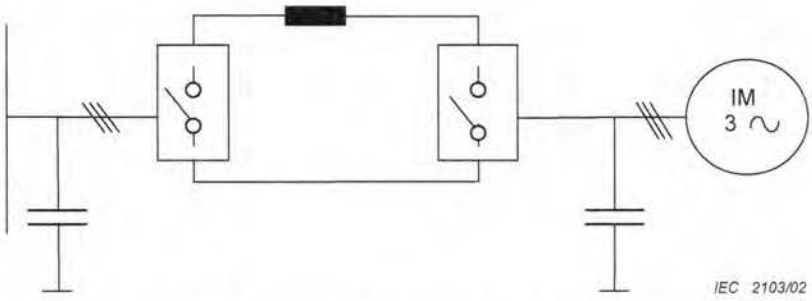


Figure A.4 – Dual CSI-PWM converter topology for induction motor drive system

This drive system essentially consists of:

- an input capacitor bank;
- a self-commutated line-side converter;
- a self-commutated motor-side converter;
- a d.c. reactor;
- an output capacitor bank;
- an induction motor.

The general characteristics of the drive system are:

- a four quadrant operation;
- a low motor torque ripple (negligible if the PWM technique is adopted);
- a near unity line-side power factor;
- a reduced input current harmonic content.

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A.2.5 VOLTAGE SOURCE INVERTER (VSI) DRIVE SYSTEMS WITH A SYNCHRONOUS OR INDUCTION MOTOR

The basic structure of the drive system is shown in figure A.5.

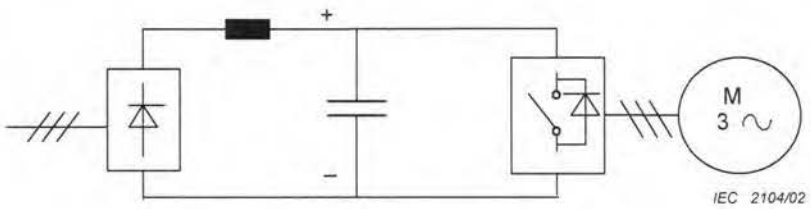


Figure A.5 – Three-phase VSI drive systems

This drive system essentially consists of:

- a diode line-side rectifier;
- a self-commutated motor-side converter;
- a d.c. reactor (if needed);
- a d.c. capacitor bank in the d.c. link;
- a synchronous or induction motor;
- an exciting system, if a synchronous motor is used.

The general characteristics of the drive are:

- a two quadrant operation;
- a low motor torque ripple (negligible if the PWM technique is adopted);
- a high line-side displacement factor.

A.2.6 VOLTAGE SOURCE THREE LEVEL, NEUTRAL POINT CLAMPED (NPC) INVERTER, DRIVE SYSTEM WITH A SYNCHRONOUS OR INDUCTION MOTOR

The basic structure is shown in figure A.6 and the detailed diagram of the NPC structure is given in figure A.7.

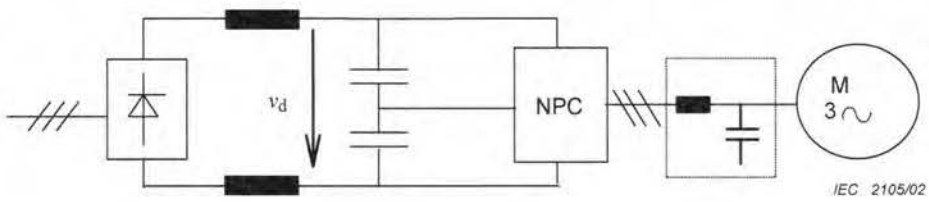


Figure A.6 – Voltage source NPC inverter drive system

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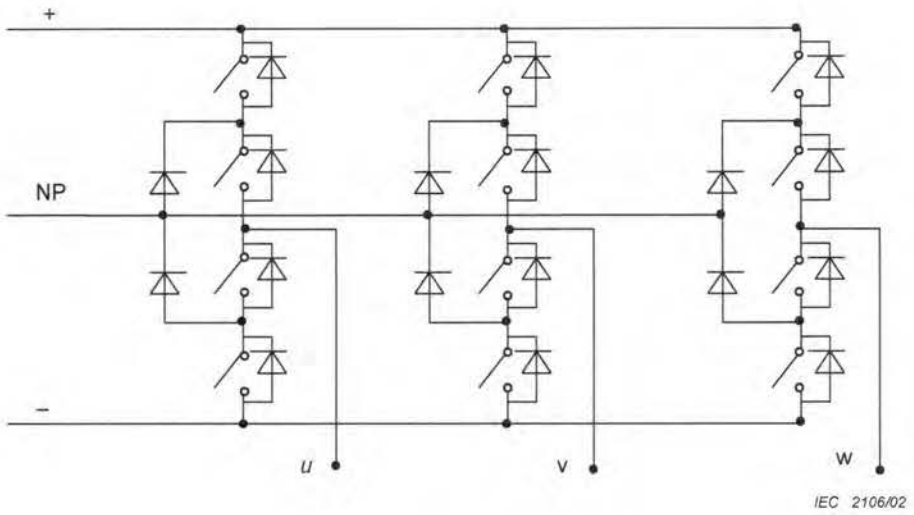


Figure A.7 – NPC structure

This drive system essentially consists of:

- a diode line-side rectifier (6p, 12p or higher);
- a self-commutated NPC motor-side inverter;
- a d.c. reactor (if needed);
- a d.c. capacitor bank;
- a synchronous or induction motor;
- an excitation system, if a synchronous motor is used.

The general characteristics of the drive system are:

- a two quadrant operation;
- a four quadrant operation when using the NPC front end converter;
- a low motor torque ripple due to the PWM technique;
- a three level PWM;
- a high line-side displacement factor;
- low line-side harmonics with a high pulse number diode rectifier.

A.2.7 VOLTAGE SOURCE MULTI-LEVEL, FLOATING SYMMETRICAL CAPACITORS (FSC) INVERTER, DRIVE SYSTEM WITH A SYNCHRONOUS OR INDUCTION MOTOR

The basic structure is shown in figure A.8 and the detailed diagram of the multi-level inverter structure is given in figure A.9.

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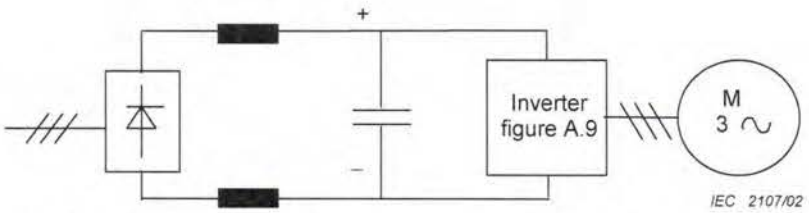


Figure A.8 – Voltage source multi-level inverter drive system

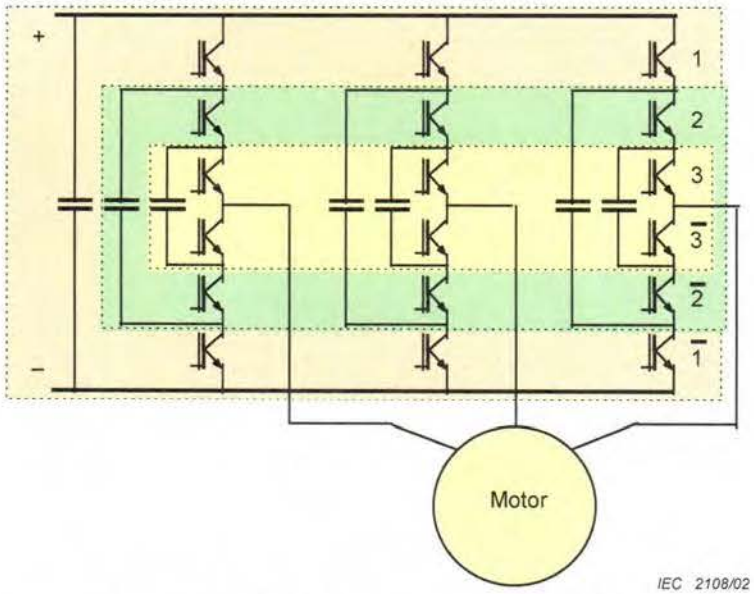


Figure A.9 – Multi-level inverter structure

This drive system essentially consists of:

- a diode line-side rectifier, generally 12-pulse;
- a d.c. reactor (if needed);
- a d.c. capacitor bank;
- a self-commutated multilevel motor-side converter, including floating symmetrical capacitors;
- a synchronous or induction motor;
- an excitation system, if a synchronous motor is used.

The general characteristics of the drive system are:

- a two quadrant operation;
- a four quadrant operation when using the multilevel inverter structure as front end converter;
- a low motor torque ripple due to the PWM technique and multilevel structure;
- a high line-side displacement factor;

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– low line-side harmonics with a high pulse number diode rectifier.

A.2.8 VOLTAGE SOURCE INVERTER, BI-DIRECTIONAL LINE-SIDE CONVERTER, WITH A SYNCHRONOUS OR INDUCTION MOTOR

The basic structure of the drive is shown in figure A.10; it has been obtained from figure A.5, by addition of a regeneration converter section. The same modification can be applied also to the NPC inverter (figure A.6) or the multilevel inverter (figure A.8).

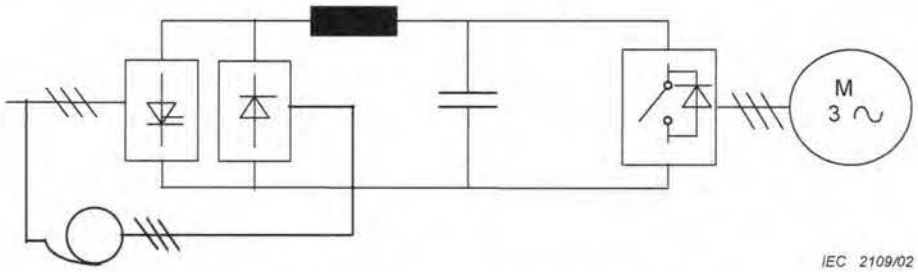


Figure A.10 – Three-phase VSI inverter with a bi-directional line-side converter

This drive system essentially consists of:

– a diode line-side rectifier;
– a line commutated line-side converter;
– a self-commutated motor-side converter;
– an auto-transformer (optional);
– a d.c. reactor (if needed);
– a d.c. capacitor bank;
– a synchronous or induction motor;
– an exciting system, if a synchronous motor is used.

The general characteristics of the drive are:

– a four quadrant operation;
– a low motor torque ripple (negligible if the PWM technique is adopted);
– a high line-side power factor in the motoring mode;
– a low line-side power factor, depending on the input power, in the regenerating mode.

A.2.9 DUAL VOLTAGE SOURCE INVERTER (VSI) DRIVE SYSTEMS WITH A SYNCHRONOUS OR INDUCTION MOTOR

The basic structure of the drive is shown in figure A.11; it has been obtained from figure A.5, replacing the diode line-side rectifier with a self-commutated inverter. The same modification can be applied also to the NPC inverter (figure A.6) or the multilevel inverter (figure A.8).

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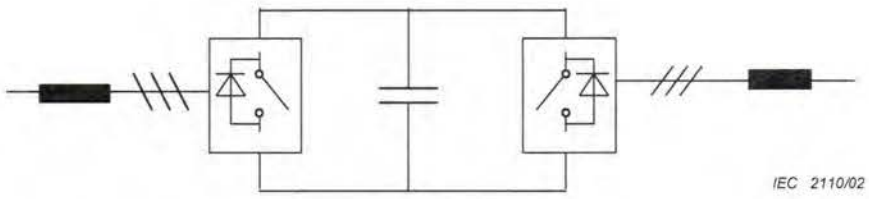


Figure A.11 – Dual voltage source inverter (VSI) drive system

This drive essentially consists of:

- a line-side reactor;
- a self-commutated line-side converter;
- a self-commutated motor-side converter;
- a d.c. capacitor bank;
- a synchronous or induction motor;
- an excitation system, if a synchronous motor is used.

The general characteristics of the drive are:

- a four quadrant operation;
- a low motor torque ripple (negligible if the PWM technique is adopted);
- a near unity line-side power factor;
- a reduced input current harmonic content.

A.2.10 VOLTAGE SOURCE MULTI-LEVEL INVERTER, MULTI-SECONDARY TRANSFORMER

The basic structure of the drive is shown in figure A.12. A detailed diagram of each power module (PM) is given in figure A.13.

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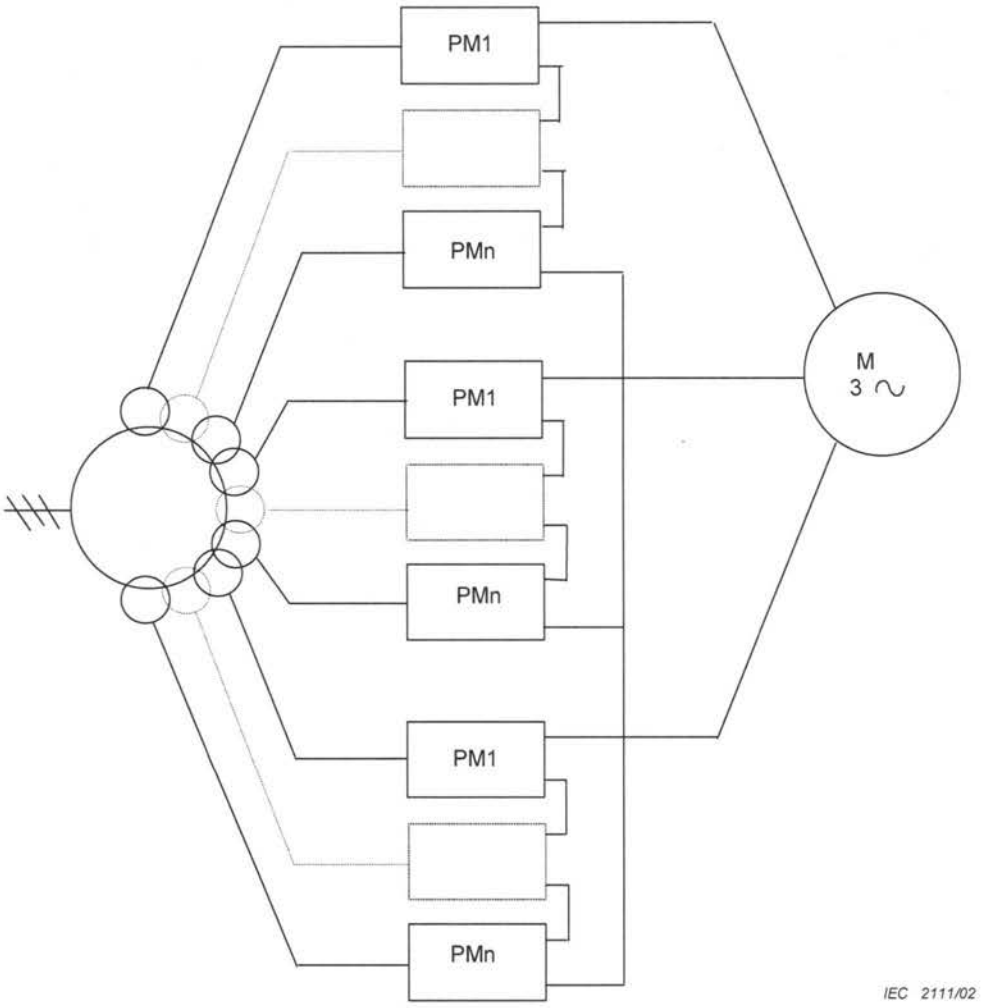


Figure A.12 – Voltage source multilevel inverter drive system

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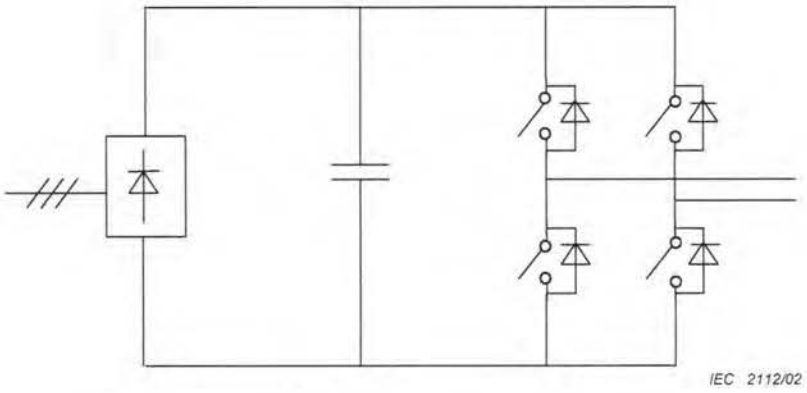


Figure A.13 – Power module (PM) for each level

This drive system essentially consists of:

- N series of connected power modules (PM) for each motor phase (each PM based on a single phase inverter, with an individual d.c. link);
- a transformer with insulated secondary voltages to supply all the power modules;
- a synchronous or induction motor;
- an excitation system, if a synchronous motor is used.

The general characteristics of the drive system are:

- a two quadrant operation;
- a low motor torque ripple (negligible if PWM technique is adopted);
- a near unity line-side power factor;
- a reduced input current harmonic content.

A.3 DRIVE SYSTEM TOPOLOGIES WITH DIRECT CONVERTERS

A.3.1 Direct converters and cycloconverters

In direct converters, conversion from an a.c. voltage of fixed amplitude and frequency to another a.c. voltage of variable amplitude and frequency is performed with no d.c. intermediate stage.

The cycloconverter represents the main example of direct converter.

The basic element is a single-phase unit consisting of two anti-parallel three-phase thyristor bridges, capable of four quadrant operation. The firing angle of each bridge is properly modulated to achieve the a.c. output voltage. A three-phase cycloconverter is composed by three single-phase units controlled to produce a.c. output voltages of the same amplitude and frequency but with phase displacements of 120°.

The cycloconverter can be operated in the circulating current mode or in the circulating current-free mode.

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A.3.2 Circulating current-free cycloconverter with a synchronous or induction motor

The basic structure of the drive is shown in figure A.14.

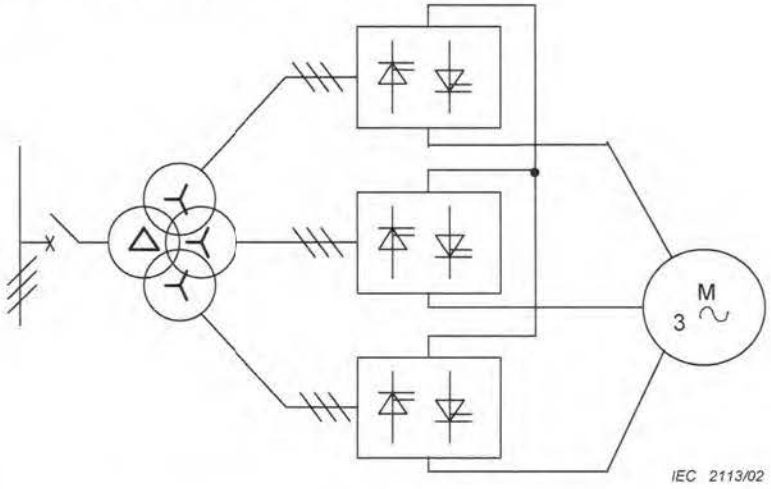


Figure A.14 – Three-phase six-pulse connection cycloconverter with a four-winding transformer

This drive system essentially consists of:

- three externally commutated reversible converters;
- a synchronous or induction motor;
- an excitation system, if a synchronous motor is used.

The general characteristics of the drive are:

- a four quadrant operation;
- a low speed operation (maximum output frequency about one third to one half of the line frequency);
- a negligible torque ripple;
- a low line-side power factor.

A.3.3 Circulating current cycloconverter with a synchronous or induction motor

The basic structure of the drive is shown in figure A.15.

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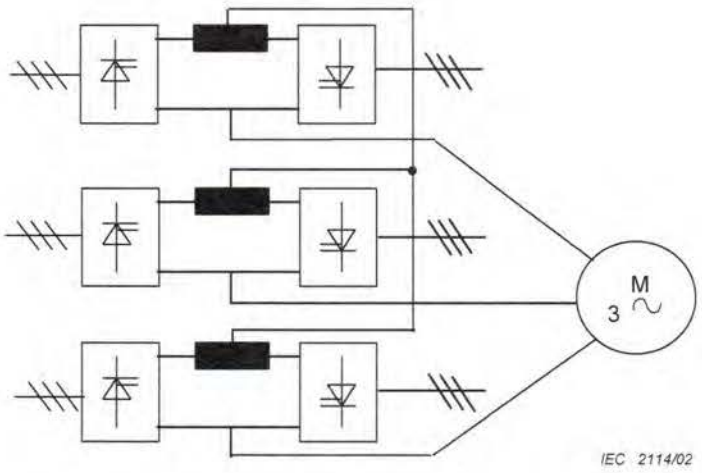


Figure A.15 – Circulating current cycloconverter

This drive system essentially consists of:

- three externally commutated reversible converters, including reactors to limit the circulating current;
- a synchronous or induction motor;
- an exciting system, if a synchronous motor is used.

The general characteristics of the drive are:

- a four quadrant operation;
- a low speed operation (maximum output frequency about 4/5 of the line frequency);
- a negligible torque ripple;
- a low line-side power factor.

A.3.4 Other configurations

Among the other drive system configurations, some are used, for example PDSs with a doubly fed induction motor, when the speed range is limited:

- static Scherbius drive systems with regeneration of the rotor slip power to the supply network;

  NOTE The Krämer drive system, for which the rotor slip power is feeding, through a diode rectifier, a d.c. shunt motor clutched on the same shaft is no longer, or rarely, used.

- four quadrant rotor fed system allowing control of a leading or lagging stator current.

These configurations offer a rating of the converter lower than the rating of the motor, according to the range of speed adjustment required below and above the synchronous speed.

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Annex B
SPEED CONTROL PERFORMANCE AND THE MECHANICAL SYSTEM
(informative)

B.1 GENERAL

There are many types of speed control strategies that are used in order to achieve the best compromise between such desirable aspects as high accuracy, fast speed responses, low torque pulsation, robustness against mechanical parameter variation, sensor-less operation, etc. The selection of the control strategy depends on the required performance of the drive system and thus the requirements of the driven equipment.

However, the performance of the speed control depends a lot on the properties of the mechanical system connected to the motor shaft. It is important to acknowledge that the supplier of the driven equipment is in many cases responsible of the performance of the speed control.

The purpose of this annex is firstly to give information about the relation between speed control performance and mechanical parameters and secondly to give guidance on the specifications of the speed control system.

B.2 BASIC SPEED CONTROL TYPES

There are basically three types of speed control systems, see figure B.1:

a) open loop control, without feedback;

b) closed loop control, with indirect (calculated) feedback. This calculation is made from electrical variables such as voltage, flux, current, pulses of the converter, etc.;

c) closed loop control, with direct (sensor) feedback.

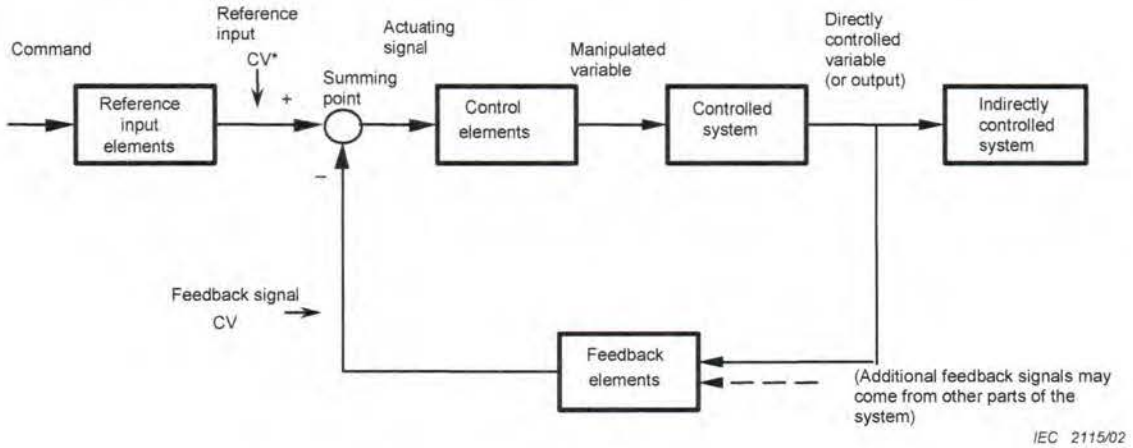


Figure B.1 – Block diagram of the feedback control system containing all the basic elements

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NOTE CV is the controlled variable, it appears in the diagram as:
– reference noted CV*,
– measurement of actual value noted CV.

B.3 EFFECT OF TORSION ELASTICITY ON SPEED CONTROL PERFORMANCE

B.3.1 Damping of the torque pulsations

When referring to torque, it is important to distinguish between:
– electromagnetic torque produced by the electrical machine (air-gap torque);
– mechanical torque on the shaft.

The latter variable involves the complete mechanical system because of load reaction. So unless otherwise specified, it is conventionally assumed that "torque" is the electromagnetic torque without considering load reaction and loss.

The connection of a motor to a driven equipment, by a shaft and/or gearing, generates a NTF (natural torsion frequency) depending on the moments of inertia and the transmission's elasticity according to the formula:

$$NTF = \frac{1}{2\pi}\sqrt{\frac{K(J_M + J_D)}{J_M J_D}}$$

where

J_M is the moment of inertia of the rotor [kgm²]

J_D is the moment of inertia of the driven equipment [kgm²]

K is the torsion stiffness [Nm/radian] ($1/K$ = elasticity)

NTF is the natural torsion frequency [Hz]

This equation refers to a two moment inertia system, see figure B.2. (A system with three or more pieces of inertia involves two or more NTFs. However, in practice only the one or two lowest NTFs are of significance).

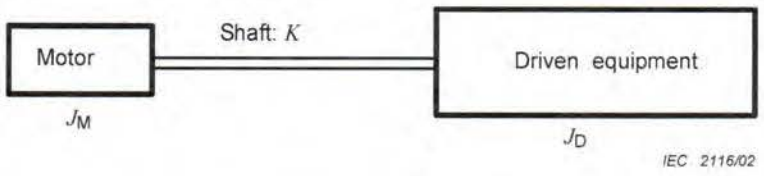


Figure B.2 – Mechanical diagram of a two moment inertia system

Pulsations in the electromagnetic torque of the motor or the load torque of the driven equipment may lead to high stresses on the shaft if the pulsation frequency is close or at one of the NTFs. This situation is especially valid for the open loop speed control.

With a closed loop speed control, however, the control system may be able to damp torsion vibrations. The requirements for successful damping are:

– the most significant NTFs are well within the bandwidth (see 7.2.3.1) of the torque controller. Typically, NTF should be less than half of the torque control bandwidth at 3dB (a rough

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estimate for the torque control bandwidth is $F_{3dB} = 0{,}5/TR$ where TR is the response time of the torque (or current) control);

- the delays in the speed measurement system are small, typically less than the rise time of the torque controller;
- the accuracy of the speed measurement system is high;
- the speed controller is tuned correctly.

The ability of the closed loop speed control to damp torsion vibrations is based on the compensation of the motor and load torque pulsations. These pulsations are compensated by counteracting changes in the torque reference. High accuracy and good dynamics of the speed measurement system are required for good damping because the compensations are based on the fast changing differences between the speed reference and the measured motor speed. These differences are usually quite small and decrease naturally with decreasing vibration level.

It is more difficult to damp load torque pulsations than motor torque pulsations. The reason is partly the complexity and partly the high attenuation of the mechanical system. The former makes the compensation difficult and the latter makes it difficult to discern the motor speed variation due to the load torque pulsation.

B.3.2 DYNAMIC PERFORMANCE OF THE SPEED CONTROL

In addition to the NTF the dynamic performance of the speed control depends on the torsion antiresonance frequency (ARF) of the mechanical system, see figure B.2:

$$ARF = \frac{1}{2\pi}\sqrt{\frac{K}{J_D}}$$

where

J_D is the moment of inertia of the driven equipment [kgm²]

K is the torsion stiffness [Nm/radian] ($1/K$ = elasticity)

ARF is the anti-resonance frequency [Hz]

This equation refers to a two moment inertia system. (A system with three or more pieces of inertia involves two or more ARFs. However, in practice only the lowest ARF is of significance).

By comparing the NTF and ARF equations, it is evident that $ARF < NTF$ always. The bigger the load to motor inertia ratio J_D/J_M is, the bigger the difference between these two frequencies will be. Note that the ARF is defined solely by the properties of the driven equipment.

There are three basic cases.

a) All NTFs and ARFs are at least one decade too high to be damped by the speed control (see the list in B.3.1).

   In this case, the dynamic performance of the speed control is determined solely by the torque controller or the speed measuring system dynamics. Note that with PDS, this case is rarely encountered because the significant NTFs and ARFs of high power equipment are typically quite low, below 20 Hz to 30 Hz. The only exception where this case may be valid is speed control systems using indirect speed feedback because of the long delays associated with speed estimation.

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b) Significant NTFs and ARFs are low enough to be damped by the speed control.

This case is most often encountered with a PDS using direct speed sensor feedback. The speed controller has to be tuned to damp the resonances in order to ensure the stability of the speed control. Thus the maximum performance of the speed control is limited by the properties of the mechanical system. The most critical is the lowest ARF. As a rule of thumb, the achievable response time of the speed controller is $1/ARF$. For example, if ARF = 10 Hz, the response time will be about 1/10 Hz = 100 ms.

c) At least one of the significant resonance frequencies is too high to be damped but not high enough to be ignored.

In order to prevent the speed controller from amplifying the resonance vibrations the speed controller has to be equipped with a filter that attenuates the resonance frequency signals. However, the drawback is that such a filter often seriously decreases the speed control dynamics.

In conclusion, it is most often not economically and technically viable to design the driven equipment for a PDS with direct speed sensor feedback in such a way that the resonance frequencies will become high enough for the case a). The dynamic performance of the case c) is often worse than that of case b), so case b) is the correct choice. Thus, in order to meet the specified dynamic speed control performance, the lowest ARF of the driven equipment has to be high enough and the control system performance has to be capable of damping the resonance frequencies.

EXAMPLE

The specified response time of the speed control is 80 ms. Thus, the required ARF should be at least 1/80 ms = 12,5 Hz. If the inertia of the driven equipment J_D is 3 000 kgm², the required torsion stiffness of the shaft should be:

$$K = J_D(2\pi\ ARF)^2 = 3.10^3(2\pi\ 12{,}5)^2 = 18{,}5\ \text{MNm/radian}$$

for a system with two pieces of inertia. If the moment of inertia of the motor is 7 000 kgm², the NTF will then be

$$NTF = \frac{1}{2\pi}\sqrt{\frac{K(J_M + J_D)}{J_M J_D}} = \frac{1}{2\pi}\sqrt{\frac{18{,}5.10^6\ (7.10^3 + 3.10^3)}{7.10^3 \times 310^3}} \approx 14{,}9\ \text{Hz}$$

In order to be able to damp the NTF, the bandwidth of the torque control F_{3dB} should be at least twice the NTF, that is 2 × 14,9 Hz ≈ 30 Hz. This specifies the maximum response time of the torque control to be $0{,}5/F_{3dB}$ = 17 ms.

NOTE This example is valid only when the assumption of two pieces of inertia connected with a shaft is valid. In practice, the mechanical system is more complex, including the inertia of the couplings and gears. Furthermore, in some cases the foundation structure under the motor and driven equipment has to be taken into account. Thus, it is better to leave the mechanical design to a specialist.

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B.4 EFFECTS OF BACKLASH

Gearing backlash introduces a non-linearity into a drive system, when there is the possibility of a torque reversal (for example a step reduction in the speed reference, demanding a slow down on a drive system, supplied by a four quadrant converter).

A torque reversal opens the backlash, causing, for a very short time, the disconnection of the motor from the driven equipment, and a resulting reduction of the system inertia on the motor shaft. Thus, the speed controller takes up the gear play (backlash) in a very short time. At this point, the system can be shocked into torsion vibration, damped out after a number of cycles (depending upon the damping factor of the system).

This temporary vibration can be reduced, but not always eliminated, by a special backlash compensation function. In processes requiring very good dynamic drive performance, it is therefore necessary to minimize the gear play.

B.5 SELECTION CRITERIA FOR THE SPEED CONTROL SYSTEM

B.5.1 Open loop speed control

There are two main advantages to open loop speed control. Firstly, it does not require a speed sensor and secondly, accurate knowledge of the motor parameter values is not needed. Thus, this kind of speed control is especially desirable for parallel connected motors and motors located far away from the BDM/CDM.

The natural and usual steady state deviation band is ±1% to ±2% (typically) for the open loop induction motor speed control (an open loop controlled synchronous motor is not a common form of PDS). If the PDS is, however, part of a closed loop control system (such as a pressure, water level, etc. control system) the deviation of the speed is corrected by the outer control loop and is thus not a problem.

Nevertheless, the dynamic stability and dynamic control performance of open loop speed control are poor, which excludes its use from applications that require short response times. In some instances, the limited dynamics may cause torsion vibration problems because the torsion vibrations cannot be damped. This is of concern especially when continuous low speed operation is required, because the sixth harmonic torque frequency will typically coincide with the lowest torsion resonance frequency at inverter frequency range of (5/6) Hz to (50/6) Hz, that is, about 0,8 Hz to 8 Hz.

B.5.2 Speed control with indirect feedback

The main advantages of speed control with indirect feedback are:

- no speed sensor is required;
- the steady state deviation of the speed is smaller than with an open loop control.

The drawback is that the accuracy of the estimation of an induction motor speed depends on the accuracy of the motor model parameters used. Thus, the estimation error may depend for example on the motor temperature. Moreover, at speeds lower than 10% or 15% of the base speed, the error in the motor voltage measurements starts to dominate thereby increasing the estimation error.

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With synchronous motors, the steady state performance is significantly better due to the synchronous nature of the motor. However, there may be limitations in the low speed operation of the PDS due to the voltage measurement problem mentioned above.

The dynamic performance depends much on the way the estimation is made. As a rule, the performance is better at higher motor speeds. The damping of the torsion resonance may not, however, be possible even though the motor is running at base speed or above.

Speed control with indirect feedback suits applications where good steady state performance is required against slow load torque variations.

B.5.3 Closed loop speed control

Closed loop speed control offers the best control performance. Naturally, the properties of the speed sensor and the speed control system are important when both a narrow deviation band and a small measurement delay are required.

With the closed loop control, accurate operation of the PDS is possible down to a speed of zero, regardless of the load torque. Note, however, that for example LCI (load commutated inverter) drives may still have restrictions in the low speed operation with high torque due to their operation principle.

Closed loop speed control is recommended for the dynamically demanding applications such as rolling mill drives and for applications where continuous low speed operation with high torque is required. Moreover, high performance closed loop control may be necessary for some applications in order to increase the inherently low mechanical damping of the torsion resonances.

B.6 SPECIFICATION OF THE SPEED CONTROL PERFORMANCE

The specification of the speed control performance is a difficult issue, because it is often difficult to know what the driven equipment actually requires for satisfactory operation. As a consequence, it is typical that very demanding values are specified just to be sure to be on the safe side.

However, such over specifying may lead to an increased cost of the equipment because of the high performance speed sensor required, and in some cases due to the stiffer and more expensive shaft between the motor and the driven equipment in order to obtain higher ARF.

Moreover, the specification of short response times means that the speed controller has to be tuned accordingly. This, however, means a lower stability margin for the speed control system. When new, the system may perform well with this kind of tuning. As time goes by, the backlash will increase due to the wear of the mechanical parts. The increased backlash decreases the stability margin of the speed control further and as a consequence increases the tendency for torsion vibration and further mechanical wear. Thus, the lifetime of the mechanical parts, for example spindles, couplings, gears, etc. may be shortened.

To summarize, the specification of the highest performance may not be ideal, and care has to be taken in order to find the right values for each drive.

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Annex C
POWER SEMICONDUCTOR LOSSES
(informative)

C.1 THYRISTOR

C.1.1 On-state losses (forward voltage drop loss)

At the thyristor on-state, forward current and forward drop voltage U_F cause on-state losses in a steady state.

Thyristor on-state losses can be expressed as:

$$P_{on} = U_{T0} \times I_{Tav} + r_T \times I^2_{Trms}$$

where

P_{on}	is the forward voltage drop loss or on-state loss	[W]
U_{T0}	is the thyristor on voltage (threshold forward drop voltage)	[V]
r_T	is the thyristor on-state resistance	[Ω]
I_{Tav}	is the thyristor anode current, average value	[A]
I_{Trms}	is the thyristor anode current, r.m.s. value	[A]

C.1.2 Forward leakage current loss

When forward voltage charges between the thyristor anode and cathode terminal and thyristor is maintained in the off-state, leakage current from the anode to the cathode causes forward leakage current loss. Usually forward leakage current loss is negligible, because the thyristor forward leakage current is very small.

C.1.3 Reverse leakage current loss

During the thyristor reverse blocking period, leakage current from cathode to anode causes reverse leakage current loss. Usually, reverse leakage current loss is negligible, because the thyristor reverse leakage current is very small. However, the switching losses increase in case of high voltage thyristors, or if operated at higher frequencies.

C.1.4 Switching losses (turn-on loss and turn-off loss)

Switching loss is negligible, except for high frequency output inverter or for high frequency PWM inverter use (which has recently become the field of self-commutated devices) and high voltage applications.

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C.1.5 Gate power losses

Thyristor gate power depends on gate current and gate-cathode voltage. It is typically negligible in high power applications.

C.2 GTO/GCT THYRISTOR (GATE TURN-OFF, GATE COMMUTATED TURN-OFF)

C.2.1 On-state losses (Forward voltage drop loss)

When the GTO is on-state, forward current and forward voltage drop U_T cause on loss in a steady state.

$$P_{Ton} = U_{T0} \times I_{Tav} + r_T \times I^2_{Trms}$$

where

P_{Ton}	is the forward voltage drop loss or on-state loss	[W]
U_{T0}	is the thyristor on voltage (threshold forward voltage drop)	[V]
r_T	is the thyristor on-state resistance	[Ω]
I_{Tav}	is the thyristor anode current, average value	[A]
I_{Trms}	is the thyristor anode current, r.m.s. value	[A]

C.2.2 Forward leakage current loss

When forward voltage charges between the GTO/GCT anode and cathode terminals and GTO/GCT is maintained in an off-state, leakage current from anode to cathode causes forward leakage current loss. Usually, forward leakage current loss is negligible, because GTO forward leakage current is very small.

C.2.3 Free-wheeling diode (forward voltage drop loss)

Diode on-state losses:

$$P_{Don} = U_{F0} \times I_{Fav} + r_F \times I^2_{Frms}$$

where

P_{Don}	is the forward voltage drop loss or on-state loss	[W]
U_{F0}	is the diode on voltage (threshold forward voltage drop)	[V]
r_F	is the diode on-state resistance	[Ω]
I_{Fav}	is the diode anode current, average value	[A]
I_{Frms}	is the diode anode current, r.m.s. value	[A]

C.2.4 Free wheeling diode switching losses

Diode turn-off loss.

$$P_{Dturn\,of} = \frac{1}{2} \times U \times I_{rr} \times t_{rr2} \times f_{to}$$

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where

$P_{\text{Dturn-off}}$	is the diode turn-off loss	[W]
U	is the diode reverse voltage	[V]
I_{rr}	is the diode reverse current (peak)	[A]
t_{rr2}	is the diode reverse recovery decay time	[s]
f_{to}	is the turn-off frequency of the diode which is different from the switching frequency of the inverter	[s^{-1}]

NOTE The turn-of frequency of the diode is equal to or lower than the switching frequency of the inverter, depending on the topology, on the control strategy and operating mode.

C.2.5 Gate power losses

GTO/GCT gate power depends on gate current and gate-cathode voltage. Usually, GTO/GCT requires a high gate current, as a consequence, gate loss becomes larger compared to conventional thyristor technology. Average gate loss can be measured by measuring average gate-cathode voltage ($V_{\text{g(ave)}}$) and average gate current ($I_{\text{g(ave)}}$).

C.2.6 Switching losses

$$P_{\text{switching}} = \sum \left(E_{\text{on}} + E_{\text{of f}}\right) \times f_{\text{switching}} \text{ (summation for one cycle)}$$

where

$P_{\text{switching}}$	is the switching loss	[W]
E_{on}	is the turn-on energy per switching cycle	[J]
E_{off}	is the turn-off energy per switching cycle	[J]
$f_{\text{switching}}$	is the switching frequency	[s^{-1}]

Turn-on losses:

losses generated during turn-on delay time ($t_{\text{d(on)}}$) and current rise time (t_{r}).

$$E_{\text{on}} = \int_0^{t_{\text{r}}} I \times U_{\text{D}} \times \text{d}t \text{ (for 1 switching)}$$

where

E_{on}	is the turn-on energy per switching cycle	[J]
I_{T}	is the anode current	[A]
U_{D}	is the anode-cathode voltage	[V]
t_{r}	is the current rise time	[s]

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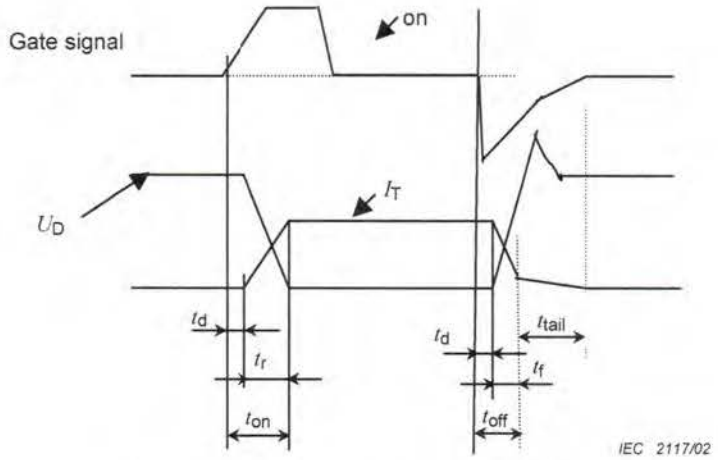


Figure C.1 – GTO/GCT switching waveform

Turn-off losses:

loss generated during turn-off delay time ($t_{d(off)}$) and current fall time (t_f).

$$E_{of\,f} = \left[\int_0^{tf} I_T \times U_D \times dt\right] + \left[I_T \times U_T \times t_{d(off)}\right] + E_d \text{ (for 1 switching)}$$

where

E_{off}	is the turn-off energy per switching cycle	[J]
E_{tl}	is the turn-off energy by tail current	[J]
I_T	is the anode current	[A]
U_D	is the anode-cathode voltage	[V]
U_T	is the GTO on voltage	[V]
t_f	is the current fall time	[s]
$t_{d(off)}$	is the turn-off delay time	[s]

For some GTO applications, a snubber regeneration circuit is essential because of GTO's large storage charge in the devices. Refer to C.4.3. Usually, in the case of GCT application, a snubber regeneration circuit is not necessary.

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C.3 IGBT

C.3.1 On loss (forward voltage drop loss)

When the IGBT turns on, the forward current and the IGBT collector – emitter saturation voltage $V_{ce(SAT)}$ cause on loss in a steady state.

$$P_{Ton} = U_{T0} \times I_{Tav} + r_T \times I^2_{Trms}$$

where

P_{Ton}	is the forward voltage drop loss or on-state loss	[W]
$U_{ce(SAT)}$	is the transistor on voltage (threshold saturation voltage drop)	[V]
r_T	is the transistor on-state resistance	[Ω]
I_{Tav}	is the transistor collector current, average value	[A]
I_{Trms}	is the transistor collector current, r.m.s. value	[A]

C.3.2 Forward leakage current loss

When the forward voltage charges between the IGBT collector and emitter terminals and the IGBT is maintained in an off-state, leakage current from collector to emitter cause forward leakage current loss. In addition, free wheeling diode reverse leakage current also causes losses.

C.3.3 Forward drop voltage loss (free wheeling diode on-state loss)

The most frequently, free wheeling diodes are assembled in IGBT modules. Usually, free wheeling diode losses cannot be measured and separated from IGBT losses.

$$P_{Don} = U_{F0} \times I_{Fav} + r_F \times I^2_{Frms}$$

where

P_{Don}	is the forward voltage drop loss or on-state loss	[W]
U_{F0}	is the diode on voltage (threshold forward voltage drop)	[V]
r_F	is the diode on-state resistance	[Ω]
I_{Fav}	is the diode anode current, average value	[A]
I_{Frms}	diode anode current, r.m.s. value	[A]

C.3.4 Free wheeling diode switching loss (free wheeling diode turn-off loss)

The most frequently, free wheeling diodes are assembled in IGBT modules. Usually, free wheeling diode losses cannot be measured and separated from IGBT losses.

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C.3.5 Gate power loss

Gate power is negligible for IGBT devices, because IGBT is a MOS-controlled device with a high gate impedance.

C.3.6 Switching loss

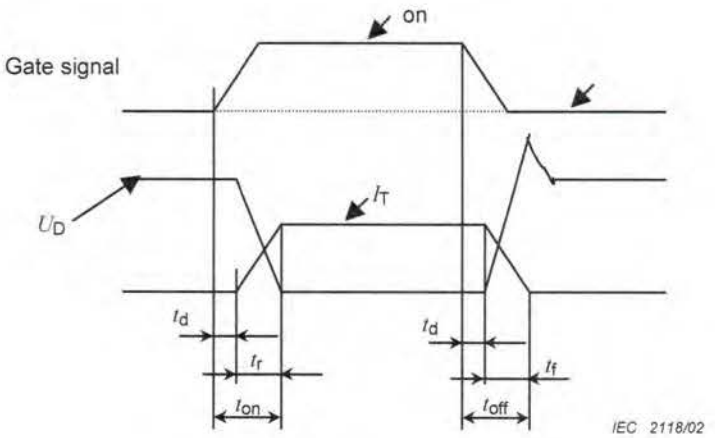


Figure C.2 – IGBT switching waveform

The switching waveform is almost the same as for GTO.

$$P_{switching} = \sum (E_{on} + E_{off}) \times f_{switching} \quad \text{(summation for 1 cycle)}$$

where

$P_{switching}$	is the switching loss	[W]
E_{on}	is the turn-on energy per switching cycle	[J]
E_{off}	is the turn-off energy per switching cycle	[J]
$f_{switching}$	is the IGBT switching frequency	[s^{-1}]

Turn-on loss:

Loss which is generated during the turn-on delay time ($t_{d(on)}$) and current rise time (t_r).

$$E_{on} = \int_0^{t_r} I_C \times U_{CE} \times dt \quad \text{(for one switching)}$$

where

E_{on}	is the turn-on energy per switching cycle	[J]
I_C	is the collector current	[A]
U_{CE}	is the collector-emitter voltage	[V]

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t_r	is the current rise time	[s]

Turn-off loss:

Loss which is generated during the turn-off delay time ($t_{d(off)}$) and current fall time (t_f).

$$E_{off} = \left[\int_0^{t_f} I_C \times U_{CE} \times dt \right] + \left[I_C \times U_{CE(SAT)} \times t_{d(off)} \right]$$

where

E_{off}	is the turn-off energy per switching cycle	[J]
I_C	is the collector current	[A]
U_{CE}	is the collector-emitter voltage	[V]
$U_{CE(SAT)}$	is the collector-emitter saturation voltage	[V]
t_f	is the current fall time	[s]
$t_{d(off)}$	is the turn-off delay time	[s]

C.5 SNUBBER LOSSES

C.4.1 Thyristor shunt snubber

Shunt snubber losses can be expressed as:

$P_{sn} = P_{lf} + P_{hf}$ (per arm)

$P_{sf} = 20 \times f^2 \times (C_s/n)^2 \times U_{LL}^2 \times R_s \times n \times (1 + 0{,}5 \sin^2 \alpha)$ (per arm)

$P_{sc} = (10{,}5/6) \times f \times (C_s/n) \times U_{LL}^2 \times [\sin^2 \alpha + \sin^2(\alpha + u)]$ (per arm)

where

P_{sn}	is the total snubber loss	[W]
P_{sf}	is the snubber loss at network frequency	[W]
P_{sc}	is the snubber loss due to commutations	[W]
R_S	is the snubber resistor	[Ω]
C_S	is the snubber capacitor	[F]
U_{LL}	is the line-line voltage at a.c. terminals of converter	[V]
f	is the converter frequency (thyristor converter – network side: power supply frequency, thyristor inverter – motor side: inverter output frequency)	[s^{-1}]
α	is the trigger delay angle	[degrees]

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u is the angle of overlap [degrees]

n is the number of thyristors in series string

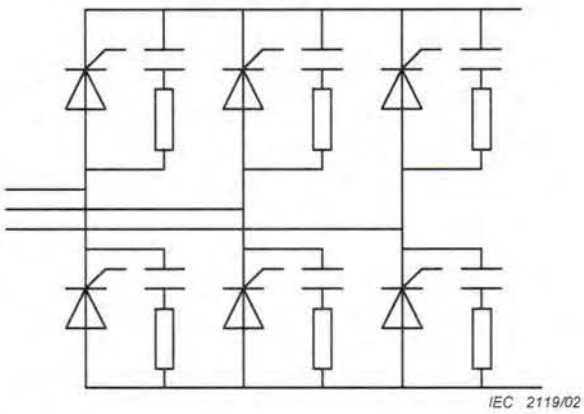


Figure C.3 – Three-phase thyristor bridge circuit

C.4.2 Voltage source inverters with common rcd clamp

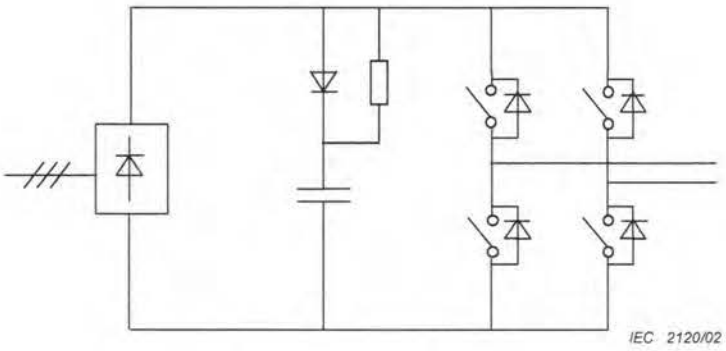


Figure C.4 – Common RCD clamp

Clamp resistor loss can be expressed as:

$$P_{rs} = \frac{L_M \times I_{off}^2 \times f_{sw}}{2}$$

where

P_{rs} is the clamp resistor loss [W]

L_M is the main circuit inductance which is effective at the switching period [H]

I_{off} is the turn off current [A]

f_{sw} is the switching frequency [s^{-1}]

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Clamp diode loss:

In the case of an RCD clamp, diode loss is negligibly small compared to resistor loss.

C.4.3 Snubber regeneration circuit loss

For certain converter circuits, it is possible to use a snubber regeneration circuit. In such a case, each component loss should be included.

C4.4 Commutation circuit loss

For a thyristor inverter, a commutation circuit is essential. Commutation circuit losses include commutation capacitor loss, commutation reactor loss, power device loss, etc.

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Annex D (U.S. Difference)
APPLICATION GUIDE FOR LINE REACTORS AND INPUT TRANSFORMERS

This annex discusses conditions that would warrant the addition of line reactors or input transformers when selecting an adjustable frequency AC motor speed converter.

D.1 CONDITION 1, VOLTAGE MATCHING

When line voltage is other than the converter input voltage, a step-up or step-down transformer, or auto transformer on the converter input may be used. The voltage transformation may be accomplished by using feeder transformers supplying mixed loads. In the case of larger converters, separate dedicated transformers may be supplied for single converters or groups of converters.

D.2 CONDITION 2, CODES

Local or plant codes may specify electrical isolation, which could include the use of transformers.

D.3 CONDITION 3, PROVIDE CONTINUITY OF SERVICE FOR INSTALLATION PRONE TO NUISANCE GROUNDING

For certain applications, engineering practice may dictate the use of ungrounded or impedance grounded branch circuits on converters and motors. Such applications are usually found in continuous process industries such as pulp and paper, food processing, chemical, cement, mining, or metals. Nuisance grounding of branch circuit conductors is common in these industries due to the effects of moisture or other environmental conditions on the branch circuit and motor insulation systems. To maintain continuity of service in a nuisance ground environment, an isolation transformer is used to galvanically isolate the converter branch circuit from the overall distribution system. In this manner, continued converter branch circuit operation is possible with a single nuisance ground. To provide continued protection, the user should clear the nuisance ground at the earliest opportunity.

The use of a transformer to provide continuity of service under nuisance ground conditions should not be confused with converter ground fault protection. Converter ground fault protection will protect the converter under ground fault conditions specified by the manufacturer but may not provide the continuity of service desired.

D.4 CONDITION, 4, LINE VOLTAGE UNBALANCE

Unbalanced voltage greater than 2 percent between phases of the incoming line may cause larger than rated line currents to be drawn from the AC line. An isolation transformer or line reactor equipped with taps may be used to compensate the voltage unbalance at all rated load conditions.

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D.5 CONDITION 5, REDUCTION OF CONVERTER INPUT HARMONIC CURRENTS

The input currents to adjustable frequency converters are generally non-sinusoidal. These non-sinusoidal currents are composed of a sinusoidal component of current at line frequency (known as the fundamental current) and additional sinusoidal components of current (known as harmonic currents) at frequencies other than the line frequency.

Since the harmonic currents do not aid in transmission of power and contribute to the volt-ampere loading of the distribution system, minimizing the magnitudes of the harmonic line currents is desirable. IEEE Standard 519 discusses in detail the effects of harmonic currents and establishes acceptable limits as to the effects of harmonic currents. The user should specify the degree of harmonic control required.

On certain types of converters, the harmonic content of the input line current may be varied by inserting impedance between the converter input and the distribution system. Transformers and line reactors are convenient devices for modifying the feeder impedance characteristics. Since the magnitude of these input harmonic currents is a function of the power conversion process within the converter, it is difficult to suggest any general guidelines for the adjustment of feeder impedance. The converter manufacturer should be consulted as to the feasibility and method of reducing the input current harmonic content to the desired level.

D.6 CONDITION 6, MINIMIZE LINE VOLTAGE NOTCHING

Adjustable speed drives utilize a solid-state input power converter connected to the AC input lines. These converters may generate a voltage transient on the AC input lines known as a line notch. Line notching generally occurs when the input line converter is operating in the continuous current conducting mode. The line notch transient is described in IEEE Standard 597. Most methods of notch area reduction involve the use of transformers or reactors to insert impedance between the distribution system and the converter input. Acceptable limits for notch area and methods of reducing the notch area are given in IEEE 519. Since the severity of the line notch transients also depends on the configuration of the controller input power converter, the user should consider this fact during application. The controller manufacturer can be consulted to determine the type of input power converter utilized and the recommended methods to reduce line notching transients.

D.7 CONDITION 7, REDUCE AVAILABLE FEEDER SHORT-CIRCUIT CAPACITY OF DRIVE CONVERTER

When the distribution feeder short circuit capacity at the converter input is greater than the converter input short-circuit withstandability level (as published on the converter nameplate), input transformers or reactors can be utilized to insert impedance between the feeder and the converter input to decrease the short-circuit capacity at the converter input terminals.

D.8 CONDITION 9, MAXIMUM/MINIMUM IMPEDANCE FOR PROPER OPERATION

D.8.1 AC source impedance

The AC source impedance is that defined at the input terminals of the converter equipment and is determined by the characteristics of the supply conductors, supply transformers, and other connected loads such as motors and capacitors.

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D.8.2 Minimum source impedance

The minimum AC source impedance to be used for proper operation of the converter equipment should be specified by the supplier. Additional impedance can be provided by series reactors or transformers or both, if needed.

NOTE: To ensure adequate equipment bracing and protective coordination, the maximum allowable AC system symmetrical short circuit current at the input terminals of the converter equipment should be specified by the supplier.

Low source impedance may cause excessive circuit dv/dt, di/dt or excessive voltage and may cause component failure.

D.8.3 Maximum source impedance

The maximum AC source impedance to be used for proper operation of the converter equipment should be specified by the supplier.

NOTE: If the maximum source impedance is exceeded, circuit voltages may have abnormal magnitudes causing component damage or commutation failure.

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