

TECHNICAL REPORT

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

Withdrawn



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TECHNICAL REPORT

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

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

**SEMICONDUCTOR CONVERTERS –
GENERAL REQUIREMENTS AND LINE COMMUTATED CONVERTERS –****Part 1-2: Application guide**

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IEC/TR 60146-1-2, which is a technical report, has been prepared by IEC technical committee 22: *Power electronic systems and equipment*.

This fourth edition cancels and replaces the third edition published in 1991. This fourth edition constitutes a technical revision.

This fourth edition includes the following main changes with respect to the previous edition:

- a) re-edition of the whole document according to the current Directives;
- b) correction of some errors.

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

Enquiry draft	Report on voting
22/170/DTR	22/173/RVC

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

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

A list of all parts of the IEC 60146 series, under the general title: *Semiconductor converters – General requirements and line commutated converters*, can be found on the IEC website.

The committee has decided that the contents of this publication will remain unchanged until the stability date indicated on the IEC web site under "<http://webstore.iec.ch>" in the data related to the specific publication. At this date, the publication will be

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- withdrawn,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

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

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SEMICONDUCTOR CONVERTERS – GENERAL REQUIREMENTS AND LINE COMMUTATED CONVERTERS –

Part 1-2: Application guide

1 Scope

This part of IEC 60146 gives guidance on variations to the specifications given in IEC 60146-1-1:2009 to enable the specification to be extended in a controlled form for special cases. Background information is also given on technical points which should facilitate the use of IEC 60146-1-1:2009.

This technical report primarily covers line commutated converters and is not in itself a specification, except as regards certain auxiliary components, in so far as existing standards may not provide the necessary data.

2 Normative references

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

IEC 60050-521:2002, *International Electrotechnical Vocabulary – Part 521: Semiconductor devices and integrated circuits*

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

IEC 60050-551-20:2001, *International Electrotechnical Vocabulary – Part 551-20: Power electronics – Harmonic analysis*

IEC 60146-1-1:2009, *Semiconductor converters – General requirements and line commutated converters Part 1-1: Specification of basic requirements*

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

IEC 60529, *Degrees of protection provided by enclosures (IP Code)*

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

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

IEC 61148, *Terminal markings for valve device stacks and assemblies and for power converter equipment*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 60146-1-1:2009, IEC 60050-551, IEC 60050-551-20, several of which are repeated here for convenience, and the following apply.

3.1 Definitions related to converter faults

3.1.1

breakthrough

failure by which a controllable valve device or an arm consisting of such devices loses its ability to block voltage during the forward blocking interval

[IEC 60050-551:1998, 551-16-60]

NOTE See Figure 1a). Breakthrough can occur in rectifier operation as well as inverter operation and for various reasons, for example excessive junction temperature, voltage surges in excess of rated peak off-state voltage, excessive rate of rise of off-state voltage or spurious gate current.

3.1.2

false firing

firing of a latching valve device or an arm consisting of such devices at an incorrect instant

[IEC 60050-551:1998, 551-16-63]

3.1.3

breakdown (of an electronic valve device or of a valve arm)

failure that permanently deprives an electronic valve device or a valve arm of its property to block voltage

[IEC 60050-551:1998, 551-16-66]

3.1.4

firing failure

failure to achieve conduction in a latching valve device or an arm consisting of such devices during the conduction interval

[IEC 60050-551:1998, 551-16-65]

NOTE See Figure 1b)

3.1.5

conduction through

in inverter operation, the situation that a valve arm continues conduction at the end of the normal conduction interval or at the end of the hold-off interval

[IEC 60050-551:1998, 551-16-64]

NOTE See Figure 1c)

3.1.6

commutation failure

failure to commutate the current from a conducting arm to the succeeding arm

[IEC 60050-551:1998, 551-16-59]

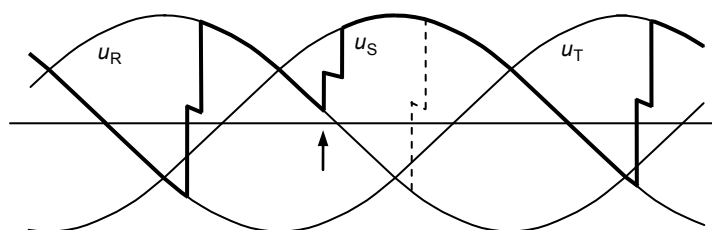
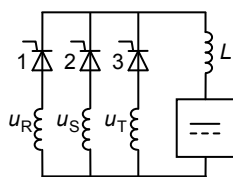


Figure 1a) Breakthrough in arm 2

IEC 2983/10

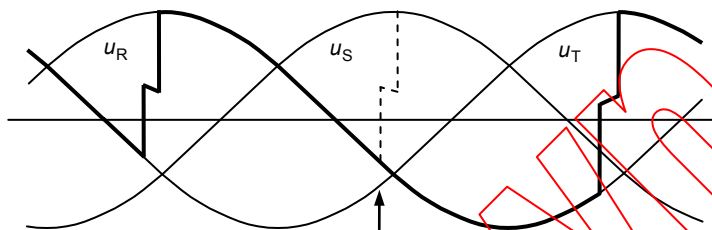


Figure 1b) Firing failure in arm 2

IEC 2984/10

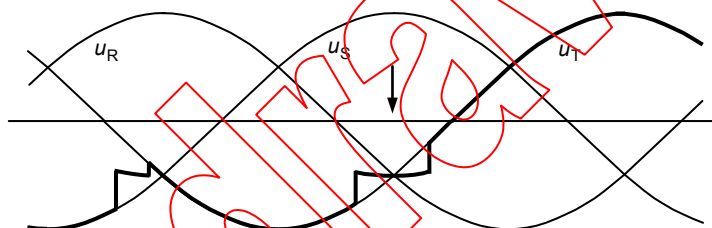


Figure 1c) Conduction through related to arm 3

IEC 2985/10

Figure 1 – Voltages at converter faults

3.2 Definitions related to converter generated transients

3.2.1

d.c. side transients

voltage transients produced by rapid changes of the d.c. voltage applied to the inductance and capacitance of the d.c. circuit

NOTE See 7.4

3.2.2

commutation transients on the line (repetitive transient)

voltage transients produced on the a.c. line after commutation

NOTE See 7.4

3.3 Definitions related to temperature

3.3.1

thermal resistance

R_{th}

quotient of the difference between the virtual junction temperature and the temperature of a specified external reference point, by the steady-state power dissipation in the device under conditions of thermal equilibrium

[IEC 60050-521:2002, 521-05-13, modified]

NOTE For most cases, the power dissipation can be assumed to be equal to the heat flow.

3.3.2

transient thermal impedance

Z_{th}

Quotient of

- a) variation of the temperature difference, reached at the end of a time interval between the virtual junction temperature and the temperature of a specified external reference point, and
- b) step function change of power dissipation at the beginning of the same time interval causing the change of temperature. Immediately before the beginning of this time interval, the distribution of temperature should have been constant with time.

NOTE Transient thermal impedance is given as a function of the time interval.

3.3.3

virtual (equivalent) junction temperature

T_j

virtual temperature of the junction of a semiconductor device

[IEC 60050-521:2002, 521-05-15]

NOTE 1 The virtual junction temperature is not necessarily the highest temperature in the semiconductor device.

NOTE 2 Based on the power dissipation and the thermal resistance or transient thermal impedance that corresponds to the mode of operation, the virtual junction temperature can be calculated using a specified relationship.

3.3.4

virtual temperature

internal equivalent temperature (of a semiconductor device)

theoretical temperature which is based on a simplified representation of the thermal and electrical behaviour of the semiconductor device

[IEC 60050-521:2002, 521-05-14]

4 Application of semiconductor power converters

4.1 Application

4.1.1 General

Semiconductor power converters are used in most industries for the conversion of electrical power and also to facilitate the conversion of mechanical, chemical or other energy into electrical power and vice versa.

They also used in electrical power utilities for the supply source conditioning.

4.1.2 Conversion equipment and systems

Examples of applications of conversion equipment and systems are as follows, and not limited in these applications.

- a) D.C. load, stabilized/adjustable voltage/current control;
- b) A.C. power controllers (a.c. or d.c. output);
- c) A.C. variable frequency:
 - line-commutated converters;

- slip energy recovery;
- machine-commutated converters;
- self-commutated converters:
 - voltage stiff (voltage source);
 - current stiff (current source);
- d) Adjustable speed drives (covered by specific IEC standards, e.g. IEC 61800-1);
- e) Uninterruptible power systems (UPS, covered by specific IEC standards, e.g. IEC 62040-3)
- f) Chemical processes (electrolysis, electroplating, electrophoresis);
- g) Computer power supplies;
- h) Traction substations, railways, tramways, mines, electric vehicles;
- i) Telephone power supplies;
- j) Electromagnets, field supplies;
- k) Radio transmitter d.c. supplies;
- l) Arc furnace d.c. power supplies;
- m) Solar photovoltaic energy conversion.

4.1.3 Supply source conditioning (active and reactive power)

Examples of supply source conditioning are as follows.

- a) HV or MV systems (transmission and distribution, reactive power compensation);
- b) LV systems (energy saving);
- c) Isolated, standby or dispersed generating plants;
- d) D.C. or a.c. supplies particularly from solar, wind or chemical energy.

NOTE Some of the applications listed above are the subject of particular IEC Publications now existing or in preparation.

4.2 Equipment specification data

4.2.1 Main items on the specification

See 6.6.2 of IEC 60146-1-1:2009: Rating plate.

4.2.2 Terminal markings

See IEC 61148.

4.2.3 Additional information

4.2.3.1 General

In addition to the essential data such as should appear on the rating plate as specified in IEC 60146-1-1:2009, the following list may prevent other important information being omitted from the specification, concerning the purchaser's requirements or the supplier's product.

4.2.3.2 Supply source

The following information is necessary to confirm the supply source conditions.

- a) Voltage and frequency (if applicable); Range of rated values, unbalance, short time outage;
- b) Short-circuit power (or description of cables, lines and transformers): minimum, statistical average, maximum values;

- c) Other existing loads (motors, capacitors, furnaces, etc);
- d) Limits of disturbances (reactive power, current harmonics, etc. prevailing or permitted);
- e) Type of earthing.

4.2.3.3 Output specification

The following information is required to design the converter connection and its control.

- a) Output voltage and frequency (if applicable);
- b) Required range of variation (continuous or stepwise);
- c) Voltage and/or current reversing capability (quadrant(s) of operation);
- d) Limits of permitted voltage/current/frequency variation;
- e) Character of load;
- f) Type of earthing.

4.2.3.4 Environment specification

The following information is required to design the cooling, structure, cubicle and so on of the converter.

- a) Temperate, tropical, arctic climates;
- b) Temperature, humidity, dust content (unless otherwise specified, IEC 60664-1, degree 1, is applicable);
- c) Unusual service conditions;
- d) Outdoor/indoor installation;
- e) Protection class (according to IEC 60529);
- f) Compliance with specific standards (IEC or others, including safety standards).

4.2.3.5 Electrical service conditions

The following informations might be duplicated with above infromations, but should be given to confirm the details.

- a) Supply bus category:
 - converter dedicated system (converters only);
 - general purpose system (includes a.c. motor loads);
 - high quality system (supplying loads with low immunity level such as computers, medical instrumentation etc.).
- b) Immunity class of the equipment: a different immunity class may be selected for one or more parameters.

4.2.4 Unusual service conditions

4.2.4.1 Abnormal temperature conditions

The preferred values of specified ambient temperature conditions are given in IEC 60146-1-1:2009, 5.2.1 to 5.2.2.

For cases where special conditions have to be considered the following is applicable.

- a) Different cooling medium temperatures may be specified for the assemblies and for the converter transformer. The values of cooling medium temperatures relating to the transformers are given in IEC 60146-1-3:1991 and those relating to assemblies are given in IEC 60146-1-1:2009.
- b) The maximum and the minimum ambient temperatures or the cooling medium temperature may be specified by the purchaser or by the supplier.

4.2.4.2 Dust and solid particle content

For particular applications the degree of pollution may be specified separately, according to IEC 60664-1 or other relevant IEC publications, for example specifying pollution classes other than degree 1 as specified in IEC 60664-1.

4.3 Converter transformers and reactors

See IEC 61378-1 or IEC 60146-1-3:1991.

4.4 Calculation factors

4.4.1 General

Calculation factors are shown in Table 1 for each converter connection. For letter symbols and definitions refer to 4.2 of IEC 60146-1-1:2009 and 4.6.2 of this technical report.

Withdrawn

Table 1 – Connections and calculation factors

No.	Transformer connection		Converter connection	p ^a	q ^a	Line side current factor ^b I _L /I _d	Valve side current factor ^c I _v /I _d	U _{di} U _{v0}	U _{IM} U _{di}	d _{xN} e _{xN}	Terminals to be short-circuited at transformers loss test			Total losses in converter operation	Terminals to be short-circuited for e _{xN}	
	Line side	Valve side									A	B	C			
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Single converter, single-way connections																
1				2	2		0,5	0,707 $\left(\frac{1}{\sqrt{2}}\right)$	0,450 $\left(\frac{\sqrt{2}}{\pi}\right)$	3,14 (π)	0,707 $\left(\frac{1}{\sqrt{2}}\right)$	0-1	0-2		0,5(P _A +P _B)	1-2
2				3	3		0,471 $\left(\frac{\sqrt{2}}{3}\right)$	0,577 $\left(\frac{1}{\sqrt{3}}\right)$	0,675 $\left(\frac{3}{\pi\sqrt{2}}\right)$	2,09 $\left(\frac{2\pi}{3}\right)$	0,866 $\left(\frac{\sqrt{3}}{2}\right)$	1-2-3			P _A +I _d ² r ₂ /3 ^d	1-2-3
3				6	6		0,816 $\left(\frac{2}{\sqrt{3}}\right)$	0,408 $\left(\frac{1}{\sqrt{6}}\right)$	1,35 $\left(\frac{3\sqrt{2}}{\pi}\right)$	2,09 $\left(\frac{2\pi}{3}\right)$	1,50 to 0,500	1-3-5	2-4-6		0,75 (P _A +P _B)	Average of measurement 1 1-3-5 measurement 2 2-4-6
4				6	6		0,816 $\left(\frac{2}{\sqrt{3}}\right)$	0,408 $\left(\frac{1}{\sqrt{6}}\right)$	1,35 $\left(\frac{3\sqrt{2}}{\pi}\right)$	2,09 $\left(\frac{2\pi}{3}\right)$	1,50 to 0,500	1-2	2-3 3-4 4-5 5-6 6-1	Avrg 1-3-5 and 2-4-6	(P _A +2P _B +3P _C)/6	Average of measurement 1 1-3-5 measurement 2 2-4-6
5				6	3		0,408 $\left(\frac{1}{\sqrt{6}}\right)$	0,289 $\left(\frac{1}{2\sqrt{3}}\right)$	0,675 $\left(\frac{3}{\pi\sqrt{2}}\right)$	2,42 $\left(\frac{4\pi}{3\sqrt{3}}\right)$	0,500	1-3-5	2-4-6		0,5 (P _A +P _B)	Average of measurement 1 1-3-5 measurement 2 4-6-2
6				6	2		0,272 $\left(\frac{1}{3\sqrt{3}}\right)$	0,236 $\left(\frac{1}{3\sqrt{2}}\right)$	0,450 $\left(\frac{\sqrt{2}}{\pi}\right)$	3,14 (π)	0,750 to 0,500	1-3-5 I-II-III	2-4-6 I-II-III		1,125 x (P _A +P _B)/2	1-4 2-5 3-6
a Refer to IEC 60146-1-1:2009, Table 2. b Refer to transformer primary. c Refer to transformer secondary. d r₂ = resistance of one cell winding																

Table 1 (continued)

No.	Transformer connection		Converter connection	p ^a	q ^a	Line side current factor ^b I_L'/I_d	Valve side current factor ^c I_v/I_d	$\frac{U_{di}}{U_{v0}}$	$\frac{U_{IM}}{U_{di}}$	$\frac{d_{xN}}{e_{xN}}$	Terminals to be short-circuited at transformers loss test			Total losses in converter operation	Terminals to be short-circuited for e_{xN}	
	Line side	Valve side									A	B	C			
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Single converter, uniform double-way connections																
7				2	2	1	1	0,900 $\left(\frac{2\sqrt{2}}{\pi}\right)$	1,57 $\left(\frac{\pi}{2}\right)$	0,707 $\left(\frac{1}{\sqrt{2}}\right)$		1-3			P_A	1-3
8				6	3	0,816 $\left(\frac{\sqrt{2}}{\sqrt{3}}\right)$	0,816 $\left(\frac{\sqrt{2}}{\sqrt{3}}\right)$	1,35 $\left(\frac{3\sqrt{2}}{\pi}\right)$	1,05 $\left(\frac{\pi}{3}\right)$	0,500		1-3-5			P_A	1-3-5
9				12	3	0,789 $\left(\frac{1+\sqrt{3}}{2\sqrt{3}}\right)$	0,408 $\left(\frac{1}{\sqrt{6}}\right)$	1,35 $\left(\frac{3\sqrt{2}}{\pi}\right)$	1,05 $\left(\frac{\pi}{3}\right)$	0,259		11-13-15	21-23-25	11-13-15 21-23-25	0,036 (P_A+P_B) + 0,928 P_C	Average of measurement 1 11-13-15 measurement 2 21-23-25
10	Same as 9, but with two different transformers		Same as 9	12	3	0,789 $\left(\frac{1+\sqrt{3}}{2\sqrt{3}}\right)$	0,408 $\left(\frac{1}{\sqrt{6}}\right)$	1,35 $\left(\frac{3\sqrt{2}}{\pi}\right)$	1,05 $\left(\frac{\pi}{3}\right)$	0,519					1,07 P_C	11-13-15 21-23-25
11				12	3	0,789 $\left(\frac{1+\sqrt{3}}{2\sqrt{3}}\right)$	0,408 $\left(\frac{1}{\sqrt{6}}\right)$	1,35 $\left(\frac{3\sqrt{2}}{\pi}\right)$	1,05 $\left(\frac{\pi}{3}\right)$	0,259		Avg. 11-13-15 and 21-23-25	21-13 23-15 25-11	11-21 13-23 15-25	1,34 P_A - 0,08 P_B - 0,27 P_C	Average of measurement 1 11-13-15 measurement 2 21-22-25
12				12	3	1,577 $\left(\frac{1+\sqrt{3}}{\sqrt{3}}\right)$	0,816 $\left(\frac{\sqrt{2}}{\sqrt{3}}\right)$	2,70 $\left(\frac{6\sqrt{2}}{\pi}\right)$	0,524 $\left(\frac{\pi}{6}\right)$	0,259		11-13-15	21-23-25	11-13-15 21-23-25	0,036 (P_A+P_B) + 0,928 P_C	Average of measurement 1 11-13-15 measurement 2 21-23-25
13	Same as 12, but with two different transformers		Same as 12	12	3	1,577 $\left(\frac{1+\sqrt{3}}{\sqrt{3}}\right)$	0,816 $\left(\frac{\sqrt{2}}{\sqrt{3}}\right)$	2,70 $\left(\frac{6\sqrt{2}}{\pi}\right)$	0,524 $\left(\frac{\pi}{6}\right)$	0,519					1,07 P_C	11-13-15 21-23-25
a Refer to IEC 60146-1-1:2009, Table 2. b Refer to transformer primary. c Refer to transformer secondary.																

Table 1 (continued)

No.	Transformer connection		Converter connection	p^a	q^a	Line side current factor ^b I_L'/I_d	Valve side current factor ^c I_v/I_d	$\frac{U_{di}}{U_{v0}}$	$\frac{U_{IM}}{U_{di}}$	$\frac{d_{xIN}}{e_{xN}}$	Terminals to be short-circuited at transformers loss test			Total losses in converter operation	Terminals to be short-circuited for e_{xN}	
	Line side	Valve side									A	B	C			
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Single converter, non-uniform double-way connections																
14				2	2		$\sqrt{\frac{\pi-\alpha}{\pi}}$	$\sqrt{\frac{\pi-\alpha}{\pi}}$	$0,900 \left(\frac{2\sqrt{2}}{\pi} \right)$	$1,57 \left(\frac{\pi}{2} \right)$	$0,707^d \left(\frac{1}{\sqrt{2}} \right)$	1-3			P_A	1-3
15				6	3		See 4.4.3	See 4.4.4	$1,35 \left(\frac{3\sqrt{2}}{\pi} \right)$	$1,05 \left(\frac{\pi}{3} \right)$	0,500	1-3-5			P_A	1-3-5
Double converter connections																
16				See connection No. 5												
17				See connection No. 5												
18				See connection No. 8												
19				See connection No. 8												
a Refer to IEC 60146-1-1:2009, Table 2. b Refer to transformer primary. c Refer to transformer secondary. d $\alpha < \mu$: $0,707 \left(1/\sqrt{2} \right)$; $\alpha > \mu$ $0,354 \left(1/(2\sqrt{2}) \right)$; $\cos \mu = 1 - X_t \times I_d / (\sqrt{2} \times U_{v0})$																

4.4.2 Voltage ratios

Table 1 gives the ratios:

column 10 column 11

$$\frac{U_{di}}{U_{v0}} \qquad \frac{U_{iM}}{U_{di}}$$

where

U_{di} is the ideal no-load direct voltage;

U_{v0} is the no-load transformer valve winding voltage;

U_{iM} is the ideal crest no-load voltage, appearing between the end terminals of an arm neglecting internal and external voltage drops in valves, at no load. The ratio remains the same at light load current close to the transition current.

NOTE For connections No. 5, No. 11 and other connections employing interphase transformers, the ratio U_{iM}/U_{di} increases at no-load.

4.4.3 Line side transformer current factor

The quotient of the r.m.s. value I'_L of the current on the line side and the direct current I_d is indicated in Table 1, column 8, on the assumption of smooth direct current, rectangular waveshape of the alternating currents and on the following voltage ratio for single or double-way connections:

$$\frac{U_L}{U_{v0}} = 1$$

where

U_L is the phase-to-phase voltage on the line side;

U_{v0} is the voltage between two commuting phases on the valve side.

For different values of the voltage ratio, the line side current is approximately:

$$I_L = I'_L \times \frac{U_{v0}}{U_L}$$

NOTE For connections 14 and 15, the line side current factor depends on the trigger delay angle α as follows:

$$0 < \alpha < \frac{\pi}{3}; \qquad \frac{I'_L}{I_d} = \sqrt{\frac{2}{3}} \approx 0,816$$

$$\frac{\pi}{3} < \alpha < \pi; \qquad \frac{I'_L}{I_d} = \sqrt{\frac{\pi - \alpha}{\pi}}$$

4.4.4 Valve-side transformer current factor

The quotient of the r.m.s. value I_v of the valve-side current in each terminal of the transformer and the direct current I_d is indicated in Table 1, column 9.

NOTE For connections 14 and 15, the valve-side current factor depends on the trigger delay angle α as follows:

$$0 < \alpha < \frac{\pi}{3}; \qquad \frac{I_v}{I_d} = \sqrt{\frac{2}{3}} \approx 0,816$$

$$\frac{\pi}{3} < \alpha < \pi; \qquad \frac{I_v}{I_d} = \sqrt{\frac{\pi - \alpha}{\pi}}$$

4.4.5 Voltage regulation

Table 1, column 12, gives the ratio:

$$\frac{d_{xtN}}{e_{xN}}$$

between the direct voltage regulation d_{xtN} at rated load due to the transformer commutating reactance, referred to U_{di} and the inductive component e_{xN} of the transformer impedance voltage at rated line current I_{LN} for the whole equipment, expressed as per unit of the rated alternating voltage U_{LN} , the secondaries being short-circuited according to column 17.

The direct inductive voltage regulation d_{xtN} can be calculated using the value of e_{xN} of a three-phase transformer only for connections with a commutating number $q \neq 3$.

For all other connections with a three-phase transformer, the ratio between d_{xtN} and e_{xN} depends on the proportions of primary and secondary reactances in the transformer.

NOTE 1 It is assumed that the angle of overlap μ is less than $2\pi/p$, p being the pulse number. See 5.1.4.

NOTE 2 For connection numbers 9, 12 and 13 the figures in column 12 assume that e_{xN} is defined for the line current of the whole equipment. If each transformer is tested separately with its rated line current ($0,816I_{dN}$ and $1,632I_{dN}$ respectively), the value of column 12 is read 0,5.

4.4.6 Magnetic circuit

The magnetic circuits corresponding to the connections supplied with three-phase currents in Table 1 are assumed to have three legs.

4.4.7 Power loss factor

Table 1, column 16, gives the relation between power losses in converter operation and on the short-circuit test at rated line current I_{LN} for the whole equipment and according to columns 13, 14 and 15.

The validity of this factor is restricted according to 4.1 of IEC 60146-1-3:1991.

4.5 Parallel and series connections

4.5.1 Parallel or series connection of valve devices

4.5.1.1 General

When diodes or thyristors are connected in series or parallel, precautions should be taken to ensure that all devices operate within rated values for voltage and current

4.5.1.2 Current balancing of parallel connected valve devices

Unequal current distribution may be caused by differences in forward voltage or on-state voltage drop and by differences in thyristor turn-on time and trigger delay angles. Differences in the impedances of the parallel arms are also of considerable influence.

If factory matching of forward or on-state characteristics and turn-on time properties of the valve devices is used for current balancing, this should be stated by the equipment supplier.

4.5.1.3 Voltage division for series connected valve devices

Unequal voltage distribution may be caused by differences in reverse and off-state characteristics, differences in the turn-on instant for thyristors and differences in recovery charge.

4.5.2 Parallel or series connection of assemblies and equipment units

4.5.2.1 General

Precautions also should be taken when assemblies and equipment units are connected in series or parallel.

4.5.2.2 Parallel connection

When units are connected in parallel, it shall be considered if they are provided with means for voltage adjustment or not.

a) Units not provided with means for voltage adjustment:

In the case of equipment units designed for parallel connection, none of the parallel connected units shall exceed its rating when operating at total rated output.

If the equipment is required to operate in parallel with other sources having dissimilar characteristics, the requirements for load-sharing should be specified separately.

b) Units provided with means for output voltage adjustment:

For such equipment, when required to operate in parallel the requirements for load sharing should be specified separately.

4.5.2.3 Series connection

When assemblies or equipment units are designed for series connection, precaution should be taken to ensure that each unit operates within its limits of rated voltages, even if the a.c. side is disconnected and the d.c. side is still connected to an active load.

In the case of series connection, the voltage to ground may be considerably higher than the voltage between the terminals. In this case, the insulation should be designed and tested accordingly.

4.6 Power factor

4.6.1 General

For converters with a pulse number of 6 or more, the total power factor is of limited interest. The value which is useful for normal purposes is the displacement factor $\cos \phi_1$ of the fundamental wave.

The displacement factor $\cos \phi_1$ is referred to the line side of the converter transformer.

For this reason, if a guarantee is required, it should, unless otherwise specified, refer to the displacement factor calculated under the assumption of both symmetrical and sinusoidal voltage.

The displacement factor for three-phase uniform thyristor connections should be determined by calculation from the measured reactances in accordance with 4.6.4.

For single-phase equipment exceeding 300 kW rated output, for equipment with non-uniform three-phase connections and for converters with sequential phase control, the method of determining the displacement factor is to be specified separately.

When a converter is operating in the rectifier mode, it is consuming active and reactive power from the a.c. system.

When a converter is operating in the inverter mode, it is delivering active power into the a.c. system but still consuming reactive power from it.

NOTE For many applications, i.e. rectifiers for small PWM (Pulse width modulated) drives with small or no d.c. reactor, the ripple influences the total power factor very much.

4.6.2 Symbols used in the determination of displacement factor

The letter symbols used in the determination of displacement factor are given in Table 2.

Table 2 – List of symbols used in the determination of displacement factor

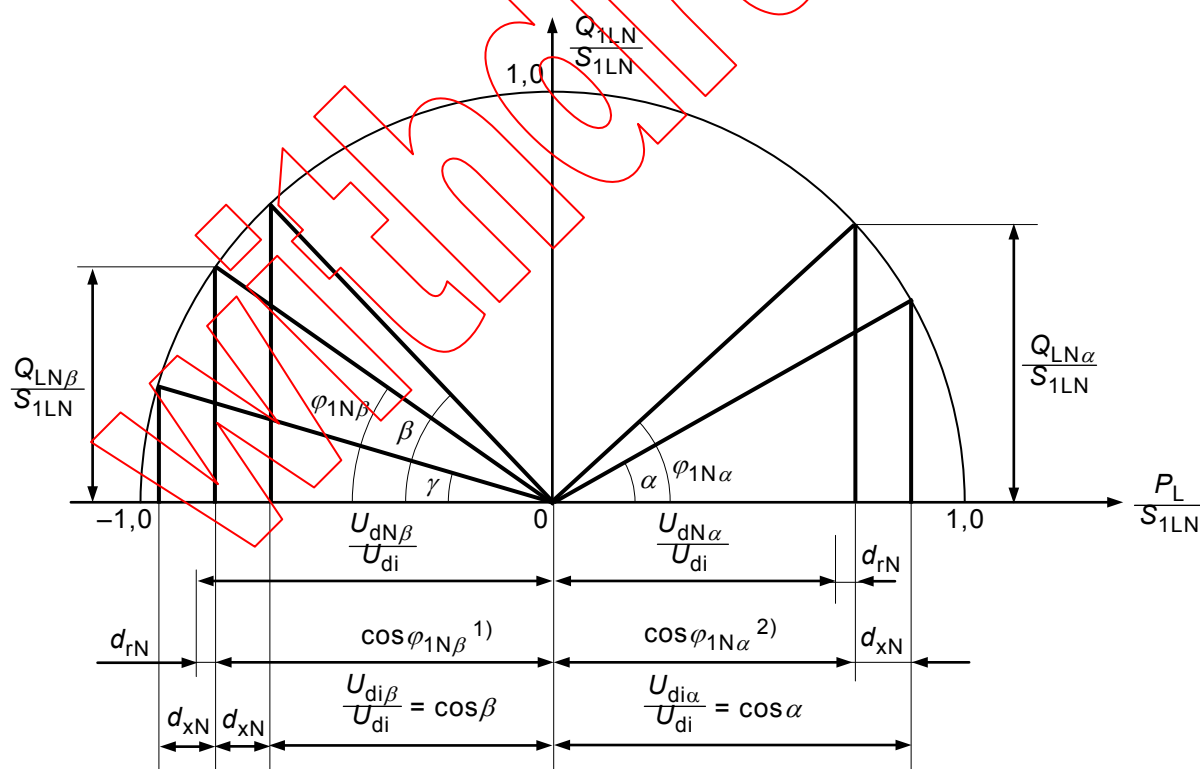
Symbol	Quantity
$\cos \varphi_{1N}$	displacement factor at rated direct current for zero trigger delay angle
$\cos \varphi_{1N\alpha}$	displacement factor at rated direct current, for trigger delay angle α
d_{rN}	$= d_{rtN} + d_{rbN}$, total resistive direct voltage regulation at rated current in per unit of U_{di}
d_{xN}	$= d_{xtN} + d_{xbN}$, total inductive direct voltage regulation at rated current in per unit of U_{di}
d_{rbN}, d_{xbN}	resistive (resp. inductive), direct voltage regulation due to other components of the converter, for example valve reactors, line side reactors and transformers etc., if any, at rated direct current, in per unit of U_{di}
d_{rtN}, d_{xtN}	resistive (resp. inductive), direct voltage regulation due to the converter transformer at rated direct current, in per unit of U_{di}
d_{LN}	additional direct voltage regulation due to a.c. system impedance, expressed in per unit of U_{di} , at rated direct current I_{dN} , when the r.m.s. voltage on line side terminals is kept constant
E_{dN}	d.c. motor counter e.m.f. at rated shaft speed and rated flux
f_{1N}	rated line frequency
I_{dN}	rated direct current
I_{LN}	Rated r.m.s. current on line side (of converter or transformer if included)
I_{1LN}	r.m.s. value of the fundamental component of I_{LN}
p	pulse number
P_{LN}	$= U_{dN} \times I_{dN} + P_{rN}$, active power on line side at rated direct current
P_{rN}	power losses in circuit resistance at rated direct current
Q_{1LN}	reactive power on line side at rated direct current, related to I_{1LN}
R_a	motor armature circuit resistance
R_C	system resistance of the supply source
R_{1SC}	short-circuit ratio referred to the fundamental apparent power of the converter
S_{1LN}	$= U_{di} \times I_{dN} = U_{LN} \times I_{1LN} \times \sqrt{3}$, apparent power on line side at rated load, based on the fundamental component I_{1LN} of the line current
S_C	short-circuit power of the supply source
S_{tN}	transformer rated apparent power
μ	angle of overlap
U_{di}	ideal no-load direct voltage
U_{dN}	rated direct voltage

Table 2 (continued overleaf)

Symbol	Quantity
U_{drN}	total resistive direct voltage regulation at rated direct current
U_{dxN}	total inductive direct voltage regulation at rated direct current
U_{dpN}	ideal internal direct voltage at rated load excluding the total resistive direct voltage regulation
X_C	system reactance of the supply source
α	trigger delay angle of phase control in rectifier operation
β	trigger advance angle of phase control in inverter operation
γ	extinction angle of commutation for inverter operation
φ_{1N}	displacement angle (of fundamental component) of the line current at rated direct current (neglecting the transformer magnetizing current)
α	suffix for rectifier operation with the trigger delay angle α
β	suffix for inverter operation with the trigger advance angle β

4.6.3 Circle diagram for the approximation of the displacement factor $\cos \varphi_{1N}$ and of the reactive power Q_{1LN} for rectifier and inverter operation

The approximate displacement factor $\cos \varphi_{1N}$ and the approximate reactive power Q_{1LN} for a converter may be estimated by use of the circle diagram given in Figure 2.



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$$1) \cos \varphi_{1N\beta} = \frac{U_{dpN\beta}}{U_{di}} = \frac{P_{1N\beta}}{S_{1LN}}$$

$$2) \cos \varphi_{1N\alpha} = \frac{U_{dpN\alpha}}{U_{di}} = \frac{P_{1N\alpha}}{S_{1LN}}$$

Figure 2 – Circle diagram for approximation of the displacement factor

4.6.4 Calculation of the displacement factor $\cos\varphi_1$

4.6.4.1 Displacement factor, at rated direct current, for zero delay angle $\cos\varphi_{1N}$

This is obtained, for the appropriate value of a.c. system reactance, from Figure 3 and Figure 4, respectively. If not otherwise stated, it is assumed that the r.m.s. value of the line side terminal voltage is kept constant.

Figure 3 is used for 6-pulse connections.

Figure 4 is used for 12-pulse connections.

The values of α_p indicated in Figure 4 are those of the inherent delay angle which occurs in a 12-pulse connection in certain operating regions, even where no phase control is applied. For phase controlled converters, they represent the minimum delay angles that can exist under the indicated conditions.

4.6.4.2 Displacement factor $\cos\varphi_{1N\alpha}$, at rated direct current, for delay angle α

If there is phase control with trigger delay angle α , the corresponding value $\cos\varphi_{1N\alpha}$ may be calculated from the following formula, which is sufficiently accurate for practical purposes:

$$\cos\varphi_{1N\alpha} = \cos\alpha - (1 - \cos\varphi_{1N})$$

For the inverter range, the displacement factor may be obtained from the following formula:

$$\cos\varphi_{1N\beta} = \cos\beta + (1 - \cos\varphi_{1N})$$

For an inverter, the abscissa in Figure 3 and Figure 4 represents the inductive direct voltage increase at rated load in per unit of U_{di} .

4.6.4.3 Displacement factor at loads other than rated load, $\cos\varphi_{1\alpha}$

When using the curves of Figure 3 and Figure 4 for other loads than the rated load, the actual values of I_d , d_{xt} and d_{xb} are used to obtain the $\cos\varphi_1$ for the actual direct current I_d .

That is, the value:

$$d_{xt} + d_{xb} = (d_{xtN} + d_{xbN}) \times \frac{I_d}{I_{dN}}$$

is used to obtain $\cos\varphi_1$ from Figure 3 and Figure 4 respectively. Then:

$$\cos\varphi_{1\alpha} = \cos\alpha - (1 - \cos\varphi_1)$$

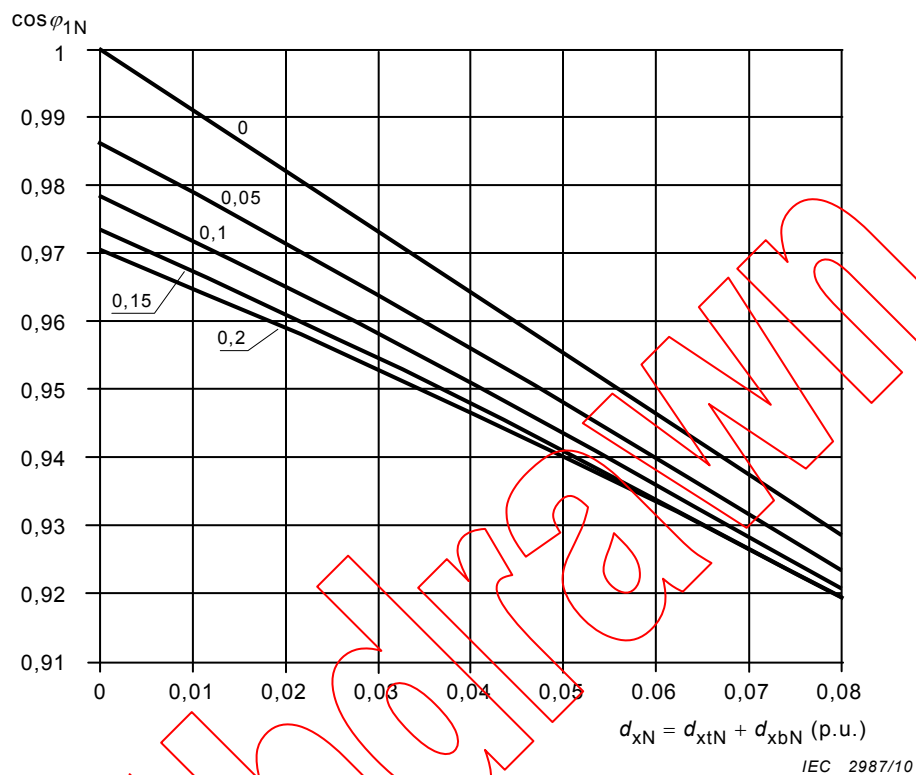


Figure 3 – Displacement factor as a function of d_{xN} for $p = 6$

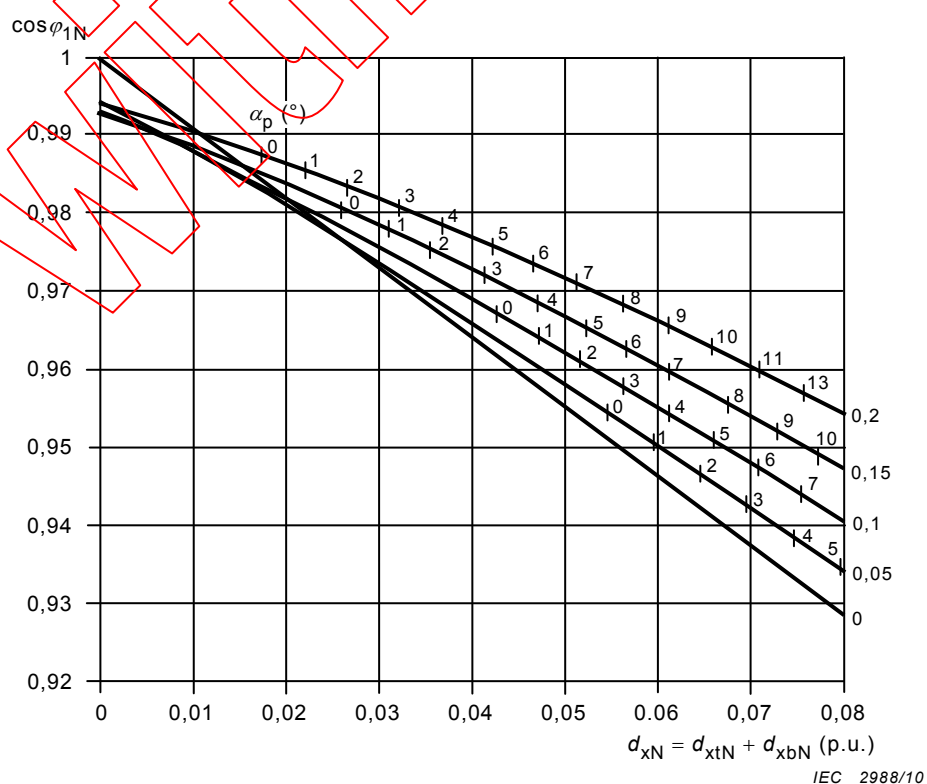


Figure 4 – Displacement factor as a function of d_{xN} for $p = 12$