

# TECHNICAL REPORT



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



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

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## INTERNATIONAL ELECTROTECHNICAL COMMISSION

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### SEMICONDUCTOR CONVERTERS – GENERAL REQUIREMENTS AND LINE COMMUTATED CONVERTERS –

#### Part 1-2: Application guidelines

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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 fifth edition cancels and replaces the fourth edition published in 2011. This edition constitutes a technical revision.

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

- a) addition of annexes concerning the applications of converter transformers and of fuses for overcurrent protection;
- b) changes of calculation methods related the inductive voltage regulation and changes of description on transformer losses to be consistent with the latest transformer standards;
- c) addition and updates of references based on the latest information.

The text of this Technical Report is based on the following documents:

| Draft T    | Report on voting |
|------------|------------------|
| 22/306/DTR | 22/310/RVDTR     |

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 document 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 document will remain unchanged until the stability date indicated on the IEC website under "<http://webstore.iec.ch>" in the data related to the specific document. At this date, the document will be

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# SEMICONDUCTOR CONVERTERS – GENERAL REQUIREMENTS AND LINE COMMUTATED CONVERTERS –

## Part 1-2: Application guidelines

### 1 Scope

This part of IEC 60146, which is a Technical Report, 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~~ facilitates the use of IEC 60146-1-1:2009.

This document 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.

This document will not take precedence on any product specific standard according to the concept shown in IEC Guide 108. IEC Guide 108 provides the information on the relationship between horizontal standards and product publications.

### 2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

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

IEC 60050-551:1998, International Electrotechnical Vocabulary – Part 551: Power electronics (available at [www.electropedia.org](http://www.electropedia.org))

IEC 60050-551-20:2001, International Electrotechnical Vocabulary – Part 551-20: Power electronics – Harmonic analysis (available at [www.electropedia.org](http://www.electropedia.org))

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 60269-1:2006, Low-voltage fuses – Part 1: General requirements

IEC 60269-4:2009, Low-voltage fuses – Part 4: Supplementary requirements for fuse-links for the protection of semiconductor devices

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, Converter transformers – Part 1: Transformers for industrial applications~~

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

IEC 61378-1:2011, *Converter transformers – Part 1: Transformers for industrial applications*

IEC/IEEE 60076-57-129, *Power transformers – Part 57-129: Transformers for HVDC applications*

### 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.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at <http://www.electropedia.org/>
- ISO Online browsing platform: available at <http://www.iso.org/obp>

NOTE Several terms from IEC 60146-1-1:2009, IEC 60050-551, IEC 60050-551-20 are repeated here for convenience.

#### 3.1 Terms and 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 1 to entry: 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.

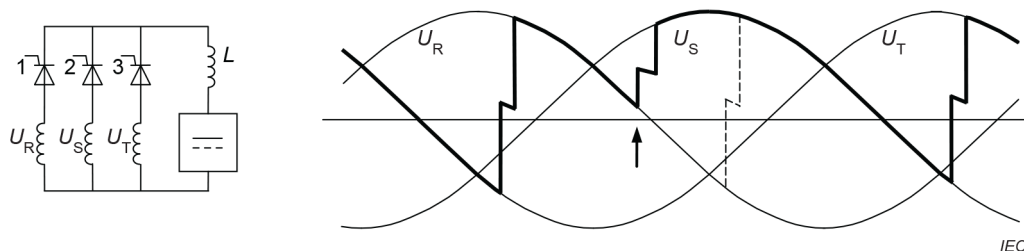


Figure 1a) Breakthrough in arm 2

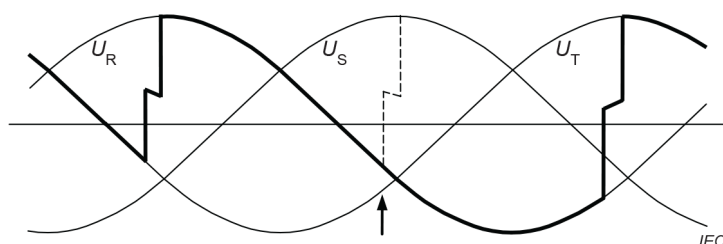


Figure 1b) Firing failure in arm 2

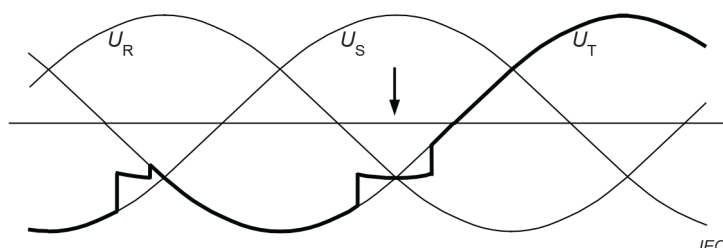


Figure 1c) Conduction through related to arm 3

Figure 1 – Voltages at converter faults

[SOURCE: IEC 60050-551:1998, 551-16-60, modified – Note 1 to entry has been added.]

### 3.1.2

#### false firing

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

[SOURCE: 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

[SOURCE: 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

Note 1 to entry: See Figure 1b).

[SOURCE: IEC 60050-551:1998, 551-16-65, modified – Note 1 to entry has been added.]

### 3.1.5 conduction through

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

Note 1 to entry: See Figure 1c).

[SOURCE: IEC 60050-551:1998, 551-16-64, modified – The definition has been rephrased, and Note 1 to entry has been added.]

### 3.1.6 commutation failure

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

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

## 3.2 Terms and definitions related to converter generated transients

### 3.2.1 DC side transients

voltage transients produced by rapid changes of the DC voltage applied to the inductance and capacitance of the DC circuit

Note 1 to entry: See 7.4.

### 3.2.2 commutation transients on the line ~~(repetitive transient)~~

voltage transients produced on the AC line after commutation

Note 1 to entry: See 7.4.

Note 2 to entry: The commutation transients are repetitive.

## 3.3 Terms and 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 1 to entry: 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

- 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
- step function change of power dissipation at the beginning of the same time interval causing the change of temperature

Note 1 to entry: Immediately before the beginning of this time interval, the distribution of temperature should have been constant with time.

Note 2 to entry: Transient thermal impedance is given as a function of the time interval.



### 3.3.3

#### **virtual equivalent junction temperature**

#### **virtual junction temperature**

$T_j$

virtual temperature of the junction of a semiconductor device

Note 1 to entry: The virtual junction temperature is not necessarily the highest temperature in the semiconductor device.

Note 2 to entry: 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.

[SOURCE: IEC 60050-521:2002, 521-05-15, modified – The symbol  $T_j$  has been added, as well as the notes to entry.]

### 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

[SOURCE: IEC 60050-521:2002, 521-05-14, modified – The notes to entry have been deleted.]

## **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) DC load, stabilized/adjustable voltage/current control;
- b) AC power controllers (AC or DC output);
- c) AC 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 DC supplies;
- l) arc furnace DC 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, **and not limited in these applications:**

- a) HV or MV systems (transmission and distribution, reactive power compensation);
- b) LV systems (energy saving);
- c) isolated, standby or dispersed generating plants;
- d) DC or AC 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 on rating plates.

### **4.2.2 Terminal markings**

**See** IEC 61148 **shall apply.**

### **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;
- g) distortion of the output waveforms.

#### 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 information might be duplicated with above information, but should be given to confirm the details.

- a) Supply bus category:
  - converter dedicated system (converters only);
  - general purpose system (includes AC 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.~~

##### 4.2.4.1 General

For the normal service conditions, refer to IEC 60146-1-1:2009, 5.2.1. In case of unusual service conditions, a special agreement between purchaser and supplier should be made according to IEC 60146-1-1:2009, 5.2.4.

##### 4.2.4.2 Cooling medium temperature difference

For the cooling medium temperature, it is noted that the temperature range of the normal service conditions is different between the converter and the transformer. Refer to IEC 61378-1:2011, 4.2, for the normal service conditions of the converter transformer.

#### **4.2.4.3 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.~~ IEC 61378-1 and IEC/IEEE 60076-57-129 shall be referred. IEC 61378-3 should be referred.

#### **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.~~



| No.                                                                                                                                                        | Transformer connection                          |            | Converter connection | $p^a$ | $q^a$ | Line side current factor <sup>b</sup><br>$I_L/I_d$ | Valve side current factor <sup>c</sup><br>$I_V/I_d$ | $\frac{U_{di}}{U_{V0}}$                   | $\frac{U_{di}}{U_{di}}$                      | $\frac{d_{iN}}{e_{iN}}$              | Terminals to be short-circuited at transformers loss test |                           |                      | Total losses in converter operation | Terminals to be short-circuited for $e_{iN}$             |
|------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------|------------|----------------------|-------|-------|----------------------------------------------------|-----------------------------------------------------|-------------------------------------------|----------------------------------------------|--------------------------------------|-----------------------------------------------------------|---------------------------|----------------------|-------------------------------------|----------------------------------------------------------|
|                                                                                                                                                            | Line side                                       | Valve side |                      |       |       |                                                    |                                                     |                                           |                                              |                                      | A                                                         | B                         | C                    |                                     |                                                          |
| 1                                                                                                                                                          | 2                                               | 3          | 4                    | 5     | 6     | 7                                                  | 8                                                   | 9                                         | 10                                           | 11                                   | 13                                                        | 14                        | 15                   | 16                                  | 17                                                       |
| Single converter, uniform double-way connections                                                                                                           |                                                 |            |                      |       |       |                                                    |                                                     |                                           |                                              |                                      |                                                           |                           |                      |                                     |                                                          |
| 7                                                                                                                                                          |                                                 |            |                      | 2     | 2     |                                                    | 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     |                                                    | $0,846 \left( \frac{2}{\sqrt{3}} \right)$           | $0,846 \left( \frac{2}{\sqrt{3}} \right)$ | $1,35 \left( \frac{3\sqrt{2}}{\pi} \right)$  | $1,05 \left( \frac{\pi}{3} \right)$  | $0,500$                                                   | 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    | $0,036(P_A+P_B) + 0,928P_C$         | 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     |                                                    | $0,789 \left( \frac{1+\sqrt{3}}{2\sqrt{3}} \right)$ | $0,408 \left( \frac{1}{\sqrt{6}} \right)$ | $1,35 \left( \frac{3\sqrt{2}}{\pi} \right)$  | $1,05 \left( \frac{\pi}{3} \right)$  | $0,519$                                                   |                           | 11-13-15-21-23-25    | $1,07P_C$                           | 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 | 21-13-23-15-11-15-25 | $1,34P_A - 0,08P_B - 0,27P_C$       | Average of measurement 1 11-13-15 measurement 2 21-22-25 |
| 12                                                                                                                                                         |                                                 |            |                      | 12    | 3     |                                                    | $1,577 \left( \frac{1+\sqrt{3}}{\sqrt{3}} \right)$  | $0,846 \left( \frac{2}{\sqrt{3}} \right)$ | $2,70 \left( \frac{6\sqrt{2}}{\pi} \right)$  | $0,524 \left( \frac{\pi}{6} \right)$ | $0,259$                                                   | 11-13-15-21-23-25         | 11-13-15-21-23-25    | $0,036(P_A+P_B) + 0,928P_C$         | 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     |                                                    | $1,577 \left( \frac{1+\sqrt{3}}{\sqrt{3}} \right)$  | $0,846 \left( \frac{2}{\sqrt{3}} \right)$ | $2,70 \left( \frac{6\sqrt{2}}{\pi} \right)$  | $0,524 \left( \frac{\pi}{6} \right)$ | $0,519$                                                   |                           | 11-13-15-21-23-25    | $1,07P_C$                           | 11-13-15-21-23-25                                        |
| <div> <div>a. Refer to IEC 60146-1-1:2009, Table 2.</div> <div>b. Refer to transformer primary.</div> <div>c. Refer to transformer secondary.</div> </div> |                                                 |            |                      |       |       |                                                    |                                                     |                                           |                                              |                                      |                                                           |                           |                      |                                     |                                                          |

| No.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            | Transformer connection |            | Converter connection | p <sup>a</sup>       | q <sup>a</sup> |   | Line-side current factor <sup>b</sup><br>$I_L/I_d$ | Valve-side current factor <sup>c</sup><br>$I_v/I_d$ | $\frac{U_{di}}{U_{V0}}$                    | $\frac{U_{IM}}{U_{di}}$           | $\frac{d_{xIN}}{e_{xN}}$                  | Terminals to be short-circuited at transformers loss test |    |    | Total losses in converter operation | Terminals to be short-circuited for $e_{xN}$ |
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                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         | 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                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   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                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |                        |            |                      | 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                                          |
| 45                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |                        |            |                      | 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                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           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| 49                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     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|                                           |                                                           |    |    |                                     |                                              |

Table 1 (1 of 4)

| No.                                      | Transformer connection                                                                |                                                                                       | Converter connection                                                                  | p <sup>a</sup> | q <sup>a</sup> | Line side fundamental current factor <sup>b,d</sup><br>$I'_{1L} / I_d$ | Line side current factor <sup>b</sup><br>$I'_L / I_d$ | Valve side current factor <sup>c</sup><br>$I_v / I_d$ | $\frac{U_{di}}{U_{v0}}$                      | $\frac{U_M}{U_{di}}$                         | $\frac{\delta qs}{g}$ | Terminals to be short-circuited for measurement <sup>d</sup> |       |    | Transformer guaranteed load losses <sup>d</sup> | Transformer guaranteed short-circuit impedance <sup>d</sup><br>$e_{XB}$ |
|------------------------------------------|---------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------|----------------|----------------|------------------------------------------------------------------------|-------------------------------------------------------|-------------------------------------------------------|----------------------------------------------|----------------------------------------------|-----------------------|--------------------------------------------------------------|-------|----|-------------------------------------------------|-------------------------------------------------------------------------|
|                                          | 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                                                   | $0,707 \left( \frac{1}{\sqrt{2}} \right)$             | $0,450 \left( \frac{\sqrt{2}}{\pi} \right)$  | $3,14 \left( \pi \right)$                    | 2                     | -                                                            | -     | -  | -                                               | -                                                                       |
| 2                                        |    |    |    | 3              | 3              | -                                                                      | $0,471 \left( \frac{\sqrt{2}}{3} \right)$             | $0,577 \left( \frac{1}{\sqrt{3}} \right)$             | $0,675 \left( \frac{3}{\pi\sqrt{2}} \right)$ | $2,09 \left( \frac{2\pi}{3} \right)$         | 3                     | -                                                            | -     | -  | -                                               | -                                                                       |
| 3                                        |    |    |    | 6              | 6              | -                                                                      | $0,816 \left( \frac{\sqrt{2}}{\sqrt{3}} \right)$      | $0,408 \left( \frac{1}{\sqrt{6}} \right)$             | $1,35 \left( \frac{3\sqrt{2}}{\pi} \right)$  | $2,09 \left( \frac{2\pi}{3} \right)$         | 6                     | -                                                            | -     | -  | -                                               | -                                                                       |
| 4                                        |    |    |    | 6              | 6              | -                                                                      | $0,816 \left( \frac{\sqrt{2}}{\sqrt{3}} \right)$      | $0,408 \left( \frac{1}{\sqrt{6}} \right)$             | $1,35 \left( \frac{3\sqrt{2}}{\pi} \right)$  | $2,09 \left( \frac{2\pi}{3} \right)$         | 6                     | -                                                            | -     | -  | -                                               | -                                                                       |
| 5                                        |  |  |  | 6              | 3              | $\frac{\sqrt{3}}{\pi \times \sqrt{2}} \quad (\approx 0,390)$           | $0,408 \left( \frac{1}{\sqrt{6}} \right)$             | $0,289 \left( \frac{1}{2\sqrt{3}} \right)$            | $0,675 \left( \frac{3}{\pi\sqrt{2}} \right)$ | $2,42 \left( \frac{4\pi}{3\sqrt{3}} \right)$ | 3/2                   | 1-3-5                                                        | 2-4-6 | -  | $\frac{P_A + P_B}{2}$                           | $e_{XA}$ and $e_{XB}$                                                   |
| 6                                        |  |  |  | 6              | 2              | -                                                                      | $0,272 \left( \frac{1}{3\sqrt{3}} \right)$            | $0,236 \left( \frac{1}{3\sqrt{2}} \right)$            | $0,450 \left( \frac{\sqrt{2}}{\pi} \right)$  | $3,14 \left( \pi \right)$                    | 2/3                   | -                                                            | -     | -  | -                                               | -                                                                       |

Table 1 (2 of 4)

| No.                                              | Transformer connection                          |            | Converter connection | p <sup>a</sup> | q <sup>a</sup> | Line side fundamental current factor <sup>b,d</sup><br>$I'_{1L} / I_d$ | Line side current factor <sup>b</sup><br>$I'_L / I_d$ | Valve side current factor <sup>c</sup><br>$I_v / I_d$ | $\frac{U_{di}}{U_{v0}}$                      | $\frac{U_{IM}}{U_{di}}$              | $\frac{\delta qs}{g}$ | Terminals to be short-circuited for short-circuit measurement <sup>d</sup> |          |                                | Transformer guaranteed load losses <sup>d</sup> | Transformer guaranteed short-circuit impedance <sup>d</sup> |
|--------------------------------------------------|-------------------------------------------------|------------|----------------------|----------------|----------------|------------------------------------------------------------------------|-------------------------------------------------------|-------------------------------------------------------|----------------------------------------------|--------------------------------------|-----------------------|----------------------------------------------------------------------------|----------|--------------------------------|-------------------------------------------------|-------------------------------------------------------------|
|                                                  | 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                                                     | $0,900 \left( \frac{2\sqrt{2}}{\pi} \right)$ | $1,57 \left( \frac{\pi}{2} \right)$  | 4                     | -                                                                          | -        | -                              | -                                               | -                                                           |
| 8                                                |                                                 |            |                      | 6              | 3              | $\frac{\sqrt{6}}{\pi}$<br>(≈0,78)                                      | $0,816 \left( \frac{2}{\sqrt{3}} \right)$             | $0,816 \left( \frac{2}{\sqrt{3}} \right)$             | $1,35 \left( \frac{3\sqrt{2}}{\pi} \right)$  | $1,05 \left( \frac{\pi}{3} \right)$  | 6                     | 1-3-5                                                                      | -        | -                              | P <sub>A</sub>                                  | e <sub>XA</sub>                                             |
| 9                                                |                                                 |            |                      | 12             | 3              | $\frac{\sqrt{6}}{\pi}$<br>(≈0,78)                                      | $0,789 \left( \frac{1+\sqrt{3}}{2\sqrt{3}} \right)$   | $0,408 \left( \frac{1}{\sqrt{6}} \right)$             | $1,35 \left( \frac{3\sqrt{2}}{\pi} \right)$  | $1,05 \left( \frac{\pi}{3} \right)$  | 3                     | 11-13-15                                                                   | 21-23-25 | 11-13-15 and 21-23-25          | P <sub>C</sub>                                  | e <sub>XA</sub> and e <sub>XB</sub>                         |
| 10                                               | Same as 9, but with two different transformers  |            | Same as 9            | 12             | 3              | $\frac{\sqrt{6}}{\pi}$<br>(≈0,78)                                      | $0,789 \left( \frac{1+\sqrt{3}}{2\sqrt{3}} \right)$   | $0,408 \left( \frac{1}{\sqrt{6}} \right)$             | $1,35 \left( \frac{3\sqrt{2}}{\pi} \right)$  | $1,05 \left( \frac{\pi}{3} \right)$  | 3                     | 11-13-15                                                                   | 21-23-25 | P <sub>A</sub> +P <sub>B</sub> | e <sub>XA</sub> and e <sub>XB</sub>             |                                                             |
| 11                                               |                                                 |            |                      | 12             | 3              | -                                                                      | $0,789 \left( \frac{1+\sqrt{3}}{2\sqrt{3}} \right)$   | $0,408 \left( \frac{1}{\sqrt{6}} \right)$             | $1,35 \left( \frac{3\sqrt{2}}{\pi} \right)$  | $1,05 \left( \frac{\pi}{3} \right)$  | 3                     | -                                                                          | -        | -                              | -                                               | -                                                           |
| 12                                               |                                                 |            |                      | 12             | 3              | $\frac{2 \times \sqrt{6}}{\pi}$<br>(≈1,559)                            | $1,577 \left( \frac{1+\sqrt{3}}{\sqrt{3}} \right)$    | $0,816 \left( \frac{2}{\sqrt{3}} \right)$             | $2,70 \left( \frac{6\sqrt{2}}{\pi} \right)$  | $0,524 \left( \frac{\pi}{6} \right)$ | 12                    | 11-13-15                                                                   | 21-23-25 | 11-13-15 and 21-23-25          | P <sub>C</sub>                                  | e <sub>XA</sub> and e <sub>XB</sub>                         |
| 13                                               | Same as 12, but with two different transformers |            | Same as 12           | 12             | 3              | $\frac{2 \times \sqrt{6}}{\pi}$<br>(≈1,559)                            | $1,577 \left( \frac{1+\sqrt{3}}{\sqrt{3}} \right)$    | $0,816 \left( \frac{2}{\sqrt{3}} \right)$             | $2,70 \left( \frac{6\sqrt{2}}{\pi} \right)$  | $0,524 \left( \frac{\pi}{6} \right)$ | 12                    | 11-13-15                                                                   | 21-23-25 | P <sub>A</sub> +P <sub>B</sub> | e <sub>XA</sub> and e <sub>XB</sub>             |                                                             |

Table 1 (3 of 4)

| No.                                                  | Transformer connection |            | Converter connection | p <sup>a</sup>       | q <sup>a</sup> | Line side fundamental current factor <sup>b,d</sup><br>I <sub>1L</sub> / I <sub>d</sub> | Line side current factor <sup>b</sup><br>I <sub>L</sub> / I <sub>d</sub> | Valve side current factor <sup>c</sup><br>I <sub>v</sub> / I <sub>d</sub> | U <sub>di</sub> / U <sub>v0</sub>               | U <sub>IM</sub> / U <sub>di</sub>      | δqs / g | Terminals to be short-circuited for short-circuit measurement <sup>d</sup> |    |    | Transformer guaranteed load losses <sup>d</sup> | Transformer short-circuit impedance <sup>e,d</sup> |
|------------------------------------------------------|------------------------|------------|----------------------|----------------------|----------------|-----------------------------------------------------------------------------------------|--------------------------------------------------------------------------|---------------------------------------------------------------------------|-------------------------------------------------|----------------------------------------|---------|----------------------------------------------------------------------------|----|----|-------------------------------------------------|----------------------------------------------------|
|                                                      | 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<br>$\left( \frac{2\sqrt{2}}{\pi} \right)$ | 1,57<br>$\left( \frac{\pi}{2} \right)$ | -       | -                                                                          | -  | -  | -                                               | -                                                  |
| 15                                                   |                        |            |                      | 6                    | 3              | -                                                                                       | See 4.4.3                                                                | See 4.4.4                                                                 | 1,35<br>$\left( \frac{3\sqrt{2}}{\pi} \right)$  | 1,05<br>$\left( \frac{\pi}{3} \right)$ | -       | -                                                                          | -  | -  | -                                               | -                                                  |
| Double converter connections                         |                        |            |                      |                      |                |                                                                                         |                                                                          |                                                                           |                                                 |                                        |         |                                                                            |    |    |                                                 |                                                    |
| 16                                                   |                        |            |                      | See connection No. 5 |                |                                                                                         |                                                                          |                                                                           |                                                 |                                        |         |                                                                            |    |    |                                                 |                                                    |
| 17                                                   |                        |            |                      | See connection No. 5 |                |                                                                                         |                                                                          |                                                                           |                                                 |                                        |         |                                                                            |    |    |                                                 |                                                    |
| 18                                                   |                        |            |                      | See connection No. 8 |                |                                                                                         |                                                                          |                                                                           |                                                 |                                        |         |                                                                            |    |    |                                                 |                                                    |
| 19                                                   |                        |            |                      | See connection No. 8 |                |                                                                                         |                                                                          |                                                                           |                                                 |                                        |         |                                                                            |    |    |                                                 |                                                    |

Table 1 (4 of 4)

|   |                                                                                                                                                                                                                                                                                                                          |
|---|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| a | Refer to IEC 60146-1-1:2009, Table 2.                                                                                                                                                                                                                                                                                    |
| b | Refer to transformer primary with voltage ratio 1.                                                                                                                                                                                                                                                                       |
| c | Refer to transformer secondary.                                                                                                                                                                                                                                                                                          |
| d | IEC 61378-1:2011, Table 1, does not contain the information for the lines 1 to 4, 6, 7, 11, 14 and 15. Then, the cells which are not given relevant values are filled with hyphen "-".<br>When the values are necessary, refer to the textbooks for the converter theory. Some information can be obtained from Annex C. |

#### 4.4.2 Voltage ratios

Table 1 gives the ratios:

| column 10               | column 11               |
|-------------------------|-------------------------|
| $\frac{U_{di}}{U_{v0}}$ | $\frac{U_{iM}}{U_{di}}$ |

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 RMS 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 commutating 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  $\alpha$  as follows:

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

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

#### 4.4.4 Valve-side transformer current factor

The quotient of the RMS 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  $\alpha$  as follows:

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

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

#### 4.4.5 Inductive direct voltage regulation due to transformer

~~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  $U_{d1}$ , 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  $q = 3$ .~~

~~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  $\mu$  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.~~

Table 1, column 12, gives the parameter:  $\frac{\delta qs}{g}$

The parameter is used to calculate the inductive voltage regulation due to the converter transformer as described in 4.7.2.4.

NOTE The ratio ( $d_{xtN}/e_{xN}$ ) in IEC 60146-1-2:2011 was removed since it uses transformer impedance value which the converter transformer standards, IEC 61378 series, do not support. Furthermore, it is not evaluated to be practical to use since the ratio is too complicated to understand. In order to show the complexity, the ratio is analysed in Annex C just for information.

#### 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.~~

#### 4.4.7 Transformer guaranteed load losses

The symbols  $P_A$ ,  $P_B$  and  $P_C$  in column 16 indicate the losses measured in each short-circuit combination A, B or C in columns 13, 14 and 15, respectively (see IEC 61378-1:2011, 7.5.1).

The contents of columns 13 to 16 of Table 1 are provided for information purpose. For the loss of the converter transformer, IEC 61378 (all parts) should be referred to.

According to IEC 61378-1:2011, 5.2 and 6.1, the transformer guaranteed load losses is the load losses measured with the rated fundamental current in short-circuit conditions indicated in columns 13 to 15 of Table 1.

The actual load loss in service includes additional loss due to non-sinusoidal converter current. This value shall be calculated in accordance with IEC 61378-1:2011, 6.2. According to IEC 61378-1:2011, 6.1, "It is not guaranteed, but shall be provided by the transformer manufacturer for the purchaser".

#### 4.4.8 Transformer guaranteed short-circuit impedance

The symbols  $e_{xA}$  and  $e_{xB}$  in column 17 show the transformer guaranteed short circuit impedance.  $e_{xA}$  is the inductive short-circuit impedance obtained by the short-circuit measurement A in column 13.  $e_{xB}$  is that obtained by the short-circuit measurement B in column 14. From these values, the commutating reactance  $X_t$  can be obtained used in the calculation for inductive voltage regulation of the transformer by the formula shown in 4.7.2.4 (see IEC 61378-1:2011, 7.2.1).

The contents of columns 13 to 15 and 17 of Table 1 are provided for information purpose. For the short-circuit impedance of the converter transformer, IEC 61378 (all parts) should be referred to.

#### 4.4.9 Line side fundamental current factor

The contents of column 7 of Table 1 are provided for information purpose. For the line side fundamental current factor of the converter transformer, IEC 61378 (all parts) should be referred to.

NOTE By comparing this factor and "line side current factor" in column 8, it is noted that the definitions of rated current are found to be different between IEC 60146 (all parts) and IEC 61378 (all parts). For more detailed explanation, refer to Annex A.

### 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 AC side is disconnected and the DC 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 AC system.

When a converter is operating in the inverter mode, it is delivering active power into the AC 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 DC 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.

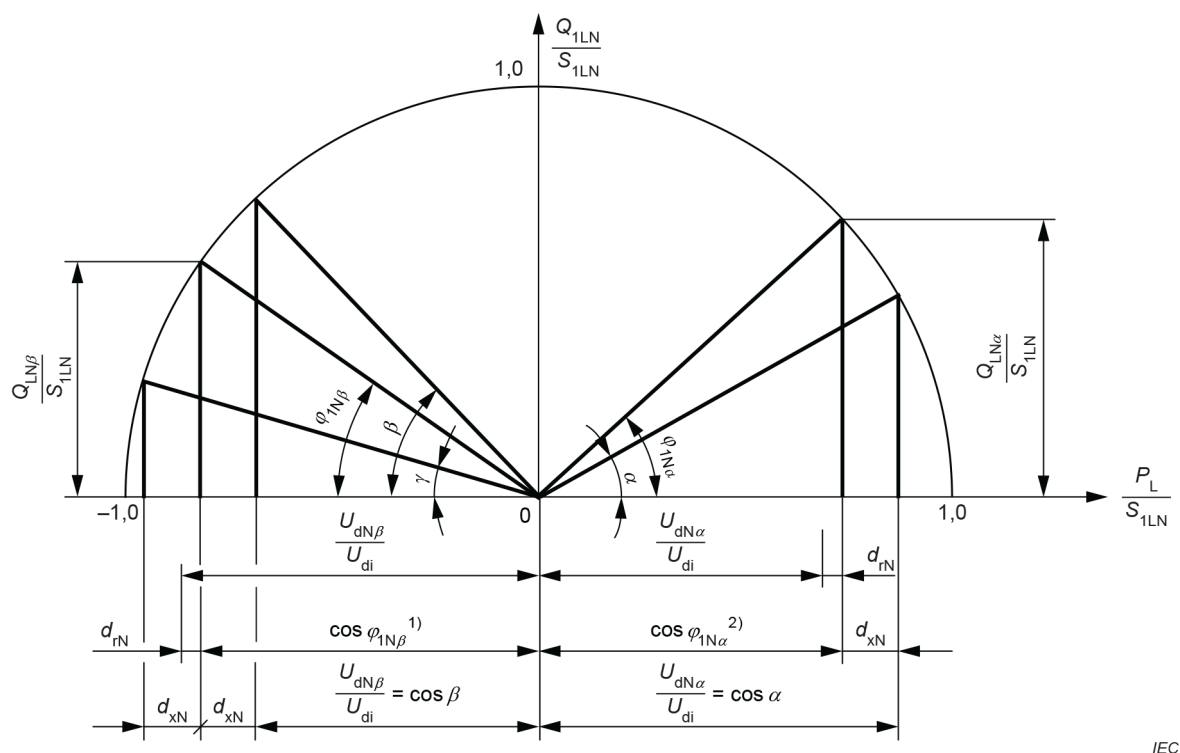
**Table 2 – List of symbols used in the determination of displacement factor**

| 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 $\alpha$                                                                                                                                                   |
| $d_{rN}$                  | $= d_{rtN} + d_{rbN}$ , 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 AC system impedance, expressed in per unit of $U_{di}$ , at rated direct current $I_{dN}$ , when the RMS voltage on line side terminals is kept constant                            |
| $E_{dN}$                  | DC 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 RMS current on line side (of converter or transformer if included)                                                                                                                                                        |
| $I_{1LN}$                 | RMS 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                                                                                                                                                                                                |
| $\mu$                     | angle of overlap                                                                                                                                                                                                                |
| $U_{di}$                  | ideal no-load direct voltage                                                                                                                                                                                                    |
| $U_{dN}$                  | rated direct voltage                                                                                                                                                                                                            |
| $U_{drN}$                 | 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                                                                                                                                                                                           |
| $\alpha$                  | trigger delay angle of phase control in rectifier operation                                                                                                                                                                     |
| $\beta$                   | trigger advance angle of phase control in inverter operation                                                                                                                                                                    |
| $\gamma$                  | extinction angle of commutation for inverter operation                                                                                                                                                                          |
| $\varphi_{1N}$            | displacement angle (of fundamental component) of the line current at rated direct current (neglecting the transformer magnetizing current)                                                                                      |

|          |                                                                      |
|----------|----------------------------------------------------------------------|
| $\alpha$ | suffix for rectifier operation with the trigger delay angle $\alpha$ |
| $\beta$  | suffix for inverter operation with the trigger advance angle $\beta$ |

#### 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.



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

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

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 AC system reactance, from Figure 3 and Figure 4, respectively. If not otherwise stated, it is assumed that the RMS 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  $\alpha_p$  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 $\alpha$

If there is phase control with trigger delay angle  $\alpha$ , 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:

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

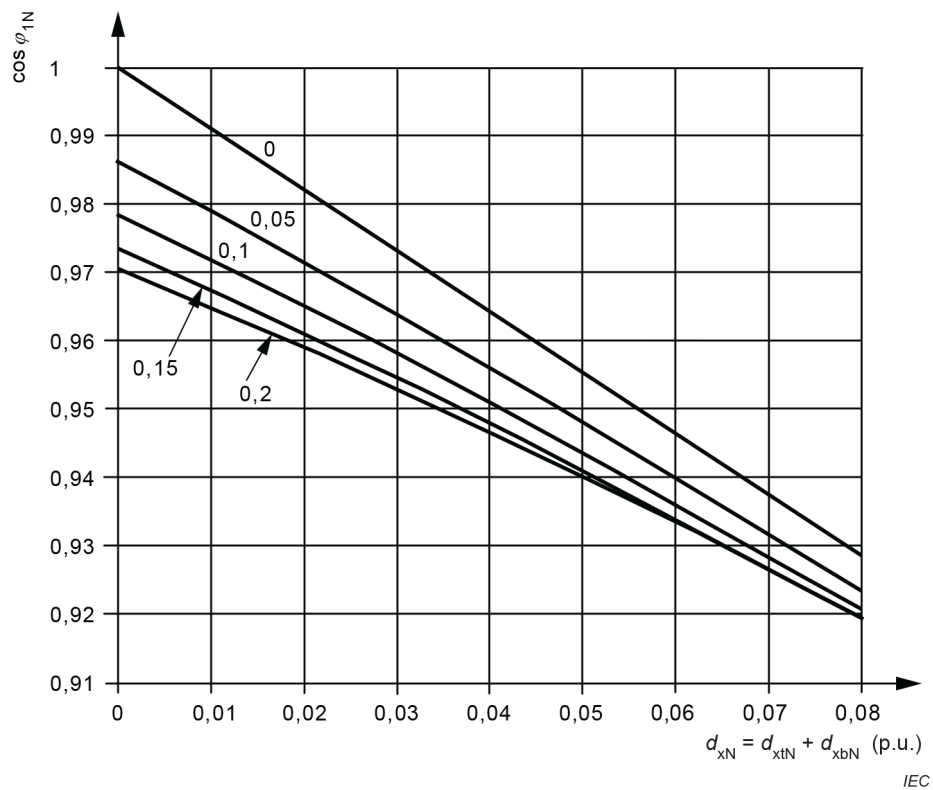


Figure 3 – Displacement factor as a function of  $d_{xN}$  for  $p = 6$

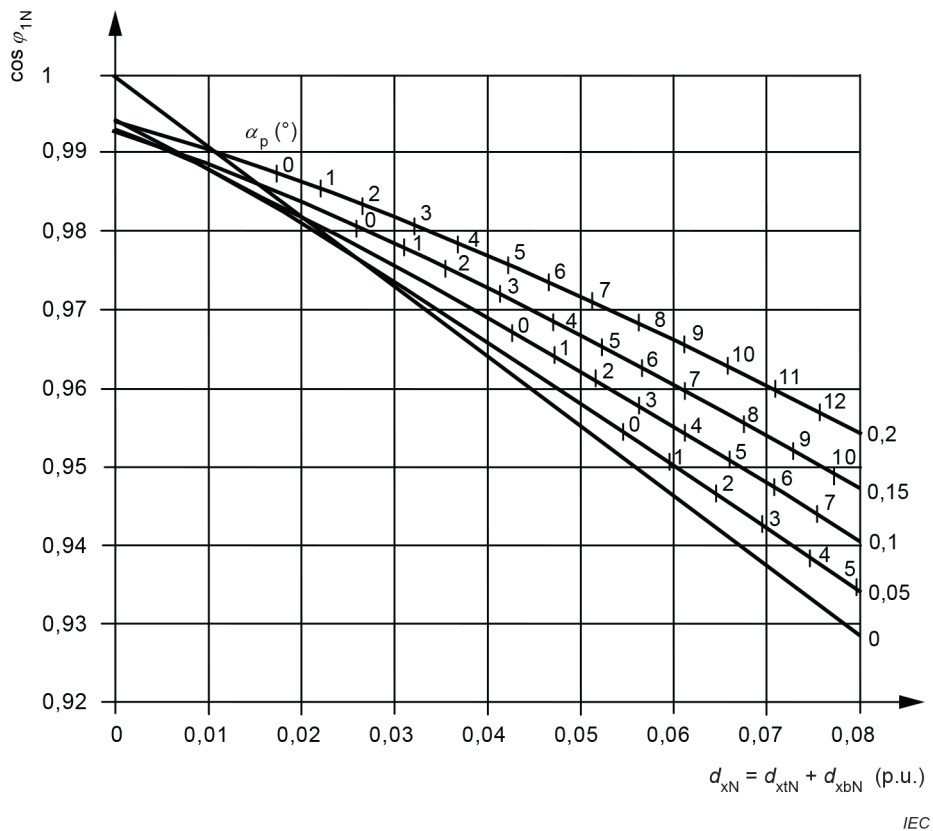


Figure 4 – Displacement factor as a function of  $d_{xN}$  for  $p = 12$

NOTE The parameter for Figure 3 and Figure 4 is:

$$\frac{1}{R_{1SC}} = \frac{S_{1LN}}{S_C} = \frac{U_{di} \times I_{dN}}{S_C}$$

#### 4.6.5 Conversion factor

For converters with a pulse number of 6 or more, the conversion factor and the power efficiency are almost equal (see IEC 60146-1-1:2009, 3.7.11 and 3.7.12).

The conversion factor should be given in addition to the power efficiency, especially for low power converters, for converters with pulse number of 6 or less if specified by the purchaser and in cases of applications where the power of the AC components of currents and voltages in the DC circuit is considered not to contribute to the useful power.

The conversion factor should always be determined by the input/output method for specified load conditions.

### 4.7 Direct voltage regulation

#### 4.7.1 General

The voltage regulation of a single converter connected to a system that does not include power factor correction capacitors is mainly due to:

- resistive voltage regulation, i.e. the voltage regulation consequential of power loss within the converter;
- inductive voltage regulation due to commutation. Commutation distorts the voltage waveform at the terminals of semiconductor assemblies and change DC voltage that is basically made up of samples of the AC voltages;
- voltage regulation due to the impedance of the line and non-sinusoidal input currents of the converter that also distort the voltage waveform at converter terminals.

The ideal no-load direct voltage  $U_{di}$  could then be referred to the voltage of the infinite bus, i.e. voltage regulation shall include the effect of all impedances existing between such infinite power source and the AC terminals of the converter.

However, this document assumes the RMS line voltage to be constant at the AC terminals of the converter, not at infinite power source.

Thus the ideal no-load direct voltage  $U_{di}$  is referred to converter terminal voltage and the voltage regulation results from two contributions:

- the inherent direct voltage regulation, i.e. the voltage regulation of the converter itself (see 4.7.2 and IEC 60146-1-1:2009, 3.7.7);
- the additional direct voltage regulation due to the influence of AC system impedance on the waveform of converter terminal voltage (see 4.7.3).

When power factor correction capacitors are included in the system, the frequency behaviour influences the voltage waveform and the voltage regulation.

#### 4.7.2 Inherent direct voltage regulation

##### 4.7.2.1 General

The inherent voltage regulation is given by the sum of the direct voltage regulation produced by the transformer and other parts of the converter equipment, such as reactors, etc., plus the change with current of on-state voltage for thyristors and forward voltage for diodes.

It is assumed that the alternating voltage at the line side terminals of the converter is constant.

The voltage regulation should refer to the principal tap of the transformer. When a thyristor converter operates in the inverter range, the voltage regulation is adding to and gives an increase of the direct voltage.

The inherent voltage regulation should be calculated from the reactances and power losses of the components of the equipment. The voltage regulation may be determined by direct measurement in an input/output load test on the equipment if so preferred by the supplier.

For single-phase equipment, for equipment with non-uniform thyristor connections and for converters with sequential phase control, the method of determining the inherent voltage regulation will be specified.

#### 4.7.2.2 Resistive direct voltage regulation due to converter transformer and interphase transformer

This regulation is given by the formula:

$$U_{\text{drtN}} = \frac{P_{\text{rtN}}}{I_{\text{dN}}}$$

where

$P_{\text{rtN}}$  is losses in the transformer windings at rated direct current.

#### 4.7.2.3 Resistive direct voltage regulation due to other components

Examples of such components are series-smoothing reactors, line side reactors, transducers, current balancing means, diodes, thyristors etc. Voltage drop by threshold voltage of valve devices is excluded.

This regulation is calculated from the formula:

$$U_{\text{drbN}} = \frac{P_{\text{rbN}}}{I_{\text{dN}}}$$

where

$P_{\text{rbN}}$  is the losses in the components at rated direct current.

#### 4.7.2.4 Inductive direct voltage regulation due to the converter transformer

~~For all connections, the inductive voltage regulation can be calculated from the transformer commutating reactance test (see IEC 60146-1-3:1991) using the formula:~~

~~$$U_{\text{dxtN}} = d_{\text{xN}} \times U_{\text{di}}$$~~

~~NOTE—The formula is not valid for multiple commutation. For connections listed in Table 1, the voltage regulation can also be calculated from the factor:  $d_{\text{xN}}/e_{\text{xN}}$  given in Table 1 and  $e_{\text{xN}}$  (see 4.4.5). In such case:~~

~~$$U_{\text{dxtN}} = \left( \frac{d_{\text{xN}}}{e_{\text{xN}}} \right) \times e_{\text{xN}} \times U_{\text{di}}$$~~

The inductive voltage regulation can be calculated from the value of  $X_l$  by means of the following formula:

$$d_{xtN} = \frac{\delta \times q \times s}{2 \times \pi \times g} \times X_t \times \frac{I_{dN}}{U_{di}}$$

where

- $g$  is the number of sets of commutating groups between which  $I_{dN}$  is divided;
- $I_{dN}$  is the rated direct current;
- $q$  is the commutation number;
- $s$  is the number of commutating groups in series;
- $U_{di}$  is the ideal no-load direct voltage;
- $\delta$  is the number of commutating groups commutating simultaneously per primary.

The parameter below used in the formula is listed in Table 1, column 12.

$$\frac{\delta \times q \times s}{g}$$

$X_t$  is the transformer commutating reactance measured according to IEC 61378-1:2011, 7.2. If the measured value of  $X_t$  is indicated in per unit (pu), it requires great attention to clarify the base of the per unit when converting the value from pu to ohm (or mili-Henry). It is noted that IEC 61378-1 defines the transformer capacity based on the fundamental component of the current. Refer to Annex A.

An alternative method to obtain the transformer inductive voltage regulation is indicated in IEC 61378-1:2011, 7.2.2.

The formula above for  $d_{xtN}$  indicates that the voltage regulation has linear characteristics to the DC load current. However, the formula can be applied when the assumptions listed below are fulfilled. For details, it is recommended to consult with textbooks of the line commutated converter theory. Refer to Bibliography.

a) Single commutation

The formula is derived based on the assumption that a single commutation takes place at an instant. In the case where multiple commutations take place, the characteristics of the voltage regulation changes from the line indicated by the formula. Such phenomena will take place when the DC load current is sufficiently large and the commutation duration extends and overwraps to the next commutation.

b) No voltage induction from DC load current

In some kinds of converter circuit with 6-pulse operation, the voltage induction in valve side windings from the DC current may take place. However, it is noted that the converter circuits listed in Table 1 are free from such phenomena.

The voltage induction from the DC load current is explained taking the converter connection No.3 as an example.

In the converter circuit, the 6 arms conduct DC current in turn for 60° each. Namely, when one of arms conducts the load current, only one valve side winding in the transformer conducts the DC load current. The magnetic field induced in the core of this winding spread to the cores of the other phases when the cores are magnetically coupled among phases.

In the case where the line side windings are connected in delta as shown in Table 1, the current is also induced in the line side winding by the magnetic field and circulates within the delta-connected windings. The circulation current cancels the magnetic field induced by the DC current flowing in the valve side winding. Then, the valve side voltage is not affected by the magnetic field made by the DC current.

However, if the line-side windings are connected in star, it results in problem. Namely, the circulation current cannot flow in the line-side windings. Then, the magnetic field induced by the DC current cannot be cancelled out and induces the voltage in the windings of the other phases. The induced voltage superimposes to the AC voltage transferred from the line side winding. The induced voltage increases as the DC current increases. Then, the voltages across the arms are distorted and the conduction periods extend longer than 60°. Namely, the operation status is different from that of 6-pulse operation. It means that the phenomena affect the inductive voltage regulation and that the previous formula for  $d_{xtN}$  cannot be applied any more.

In summary, it should be noted that the winding connection or the magnetic design of the transformer affects the inductive voltage regulation and it is recommended to pay great attention to the transformer connection when calculating the inductive voltage regulation.

#### c) Constant DC current

The formula is derived based on the assumption that the DC current is kept ideally constant.

When the DC load is very light, in practice, the DC current is not constant and intermittent. Especially, when a DC capacitor or some parasitic capacitance is connected to the DC circuit with a light load, the DC current is likely intermittent. When the DC load has characteristics keeping DC voltage by itself, like batteries, DC motors or electrolysis, the intermittent current also likely appears. In such case, the DC voltage will be higher than the voltage estimated by the formula above.

Refer to IEC 60146-1-1:2009, 4.3.2.2.

### 4.7.2.5 Inductive direct voltage regulation due to other components

For example valve reactors, line side reactors, current balancing reactors, etc.

The symbols given in Table 3 are used in the calculation formulae.

**Table 3 – List of symbols used in the calculation formulae**

| Symbol                               | Quantity                                                                                                    |
|--------------------------------------|-------------------------------------------------------------------------------------------------------------|
| $d_{xbLN}$                           | inductive direct voltage regulation at $I_{dN}$ due to line side reactors in per unit of $U_{di}$           |
| $d_{xbvN}$                           | inductive direct voltage regulation at $I_{dN}$ due to valve side reactors in per unit of $U_{di}$          |
| $U_{dxbLN}$                          | inductive direct voltage regulation, corresponding to $d_{xbLN}$                                            |
| $U_{dxbvN}$                          | inductive direct voltage regulation, corresponding to $d_{xbvN}$                                            |
| $X_{bL}$                             | reactance per phase on line side of reactor, transformer etc.                                               |
| <del><math>X_{bv}</math></del> $X_x$ | reactance per phase on valve side of reactor, valve reactors etc.                                           |
| $I_{1L}$                             | RMS value of the transformer fundamental primary phase current                                              |
| $I_{bN}$                             | RMS current in reactor, corresponding to $I_{dN}$ , calculated on the basis of rectangular current waveform |
| $I_{dN}$                             | rated direct current                                                                                        |
| $U_{bN}$                             | rated phase-to-phase voltage at the line side terminals of the reactor etc.                                 |
| $g$                                  | number of commutating groups between which $I_{dN}$ is divided                                              |
| $p$                                  | pulse number                                                                                                |
| <del><math>g</math></del> $q$        | commutation number                                                                                          |
| $s$                                  | number of commutating groups in series                                                                      |
| $\delta$                             | number of commutating groups commutating simultaneously per <del>reactor</del> primary                      |

a) For reactors, transformers etc., on the line side:

- For three-phase systems:

$$d_{xbLN} = \frac{\sqrt{3} \times I_{bN} \times X_{bL}}{U_{bN}} \sin\left(\frac{\pi}{p}\right) \text{ and } U_{dxbLN} = \frac{\sqrt{3} \times I_{bN} \times U_{di} \times X_{bL}}{U_{bN}} \sin\left(\frac{\pi}{p}\right)$$

– For single-phase systems:

$$d_{xbLN} = \frac{1}{\sqrt{2}} \times \frac{I_{bN} \times X_{bL}}{U_{bN}} \text{ and } U_{dxbLN} = \frac{1}{\sqrt{2}} \times \frac{I_{bN} \times X_{bL} \times U_{di}}{U_{bN}}$$

b) For valve side reactors:

$$d_{xbvN} = \frac{\delta \times q \times s}{2 \times \pi \times g} \times \frac{I_{dN} \times X_{bv}}{U_{di}} \text{ and } U_{dxbvN} = \frac{\delta \times q \times s}{2 \times \pi \times g} \times I_{dN} \times X_{bv}$$

The inductive direct voltage regulation due to other components is:

$$U_{dxbN} = U_{dxbLN} + U_{dxbvN}$$

#### 4.7.2.6 Inherent direct voltage regulation of the converter

The direct voltage regulation at rated direct current due to converter transformer and interphase transformer (if any), is given by:

$$U_{dtN} = U_{drtN} + U_{dxtN}$$

The direct voltage regulation at rated direct current due to other components of the converter, is given by:

$$U_{dbN} = U_{drbN} + U_{dxbN}$$

The inherent direct voltage regulation at rated direct current, is given by:

$$U_{dtN} + U_{dbN} = U_{drtN} + U_{dxtN} + U_{drbN} + U_{dxbN}$$

#### 4.7.3 Direct voltage regulation due to AC system impedance

##### 4.7.3.1 Influence of AC system impedance on DC voltage regulation of the converter

Even if the converter terminal voltage RMS value is maintained constant, the AC system impedance causes an additional voltage regulation to appear on the DC terminals of the converter.

This is a consequence of changes in waveform of converter terminal voltages, due to non-sinusoidal currents drawn by the converter that influence the voltage regulation.

This influence depends on the pulse number and the ratio ( $R_{1SC}$ ) of the short-circuit power of the source to the fundamental apparent power of the converter at rated direct current.

NOTE  $R_{SC}$  is referred to the rated apparent power in IEC 60146-1-1:2009. It is convenient to use  $R_{1SC}$  to calculate the influence of the AC system impedance.

##### 4.7.3.2 Calculation of the additional direct voltage regulation $U_{dLN}$ due to AC system impedance

Figure 5 gives the additional direct voltage regulation  $d_{LN}$  in per unit of  $U_{di}$  at rated direct current, due to AC system impedance. The corresponding voltage regulation  $U_{dLN}$  is:

$$U_{dLN} = d_{LN} \times U_{di}$$

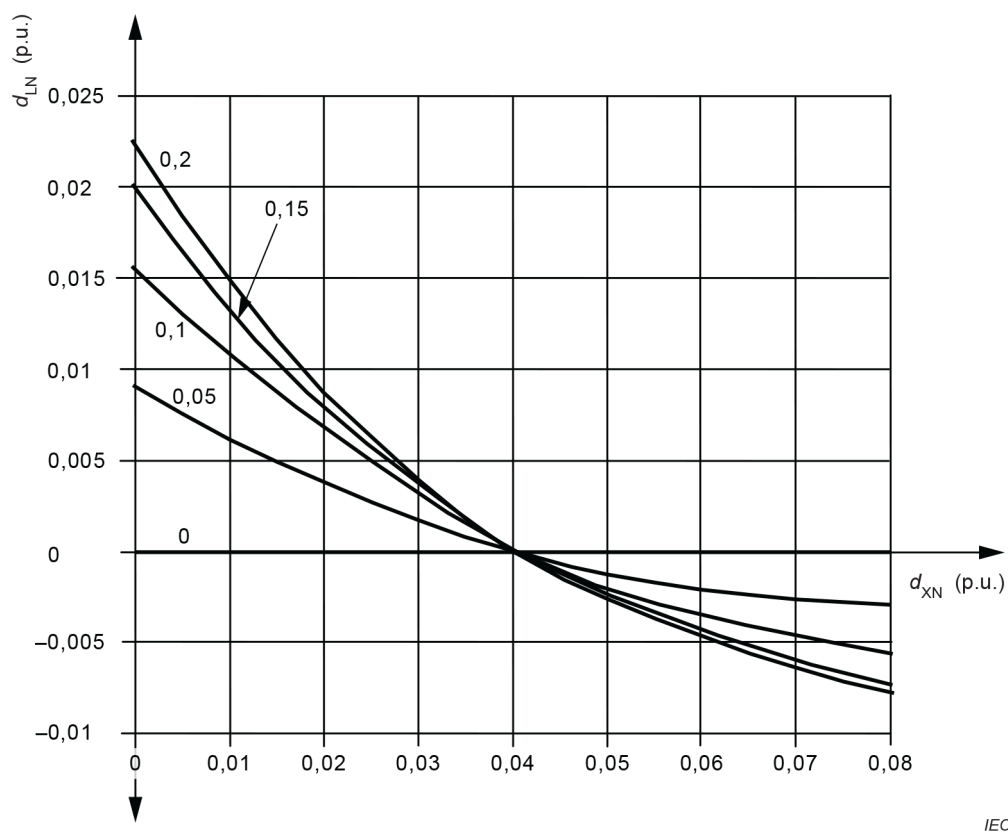
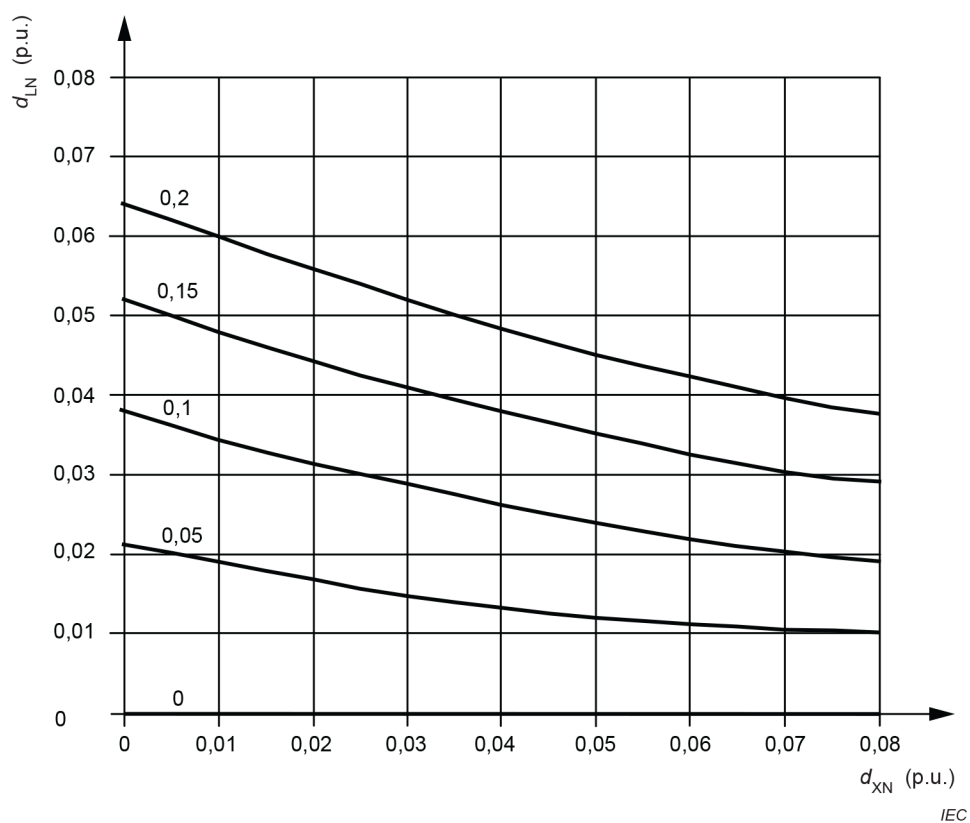
If not otherwise stated, it is assumed that the RMS value of the line side terminal voltage of the converter is kept constant.

When using the curves of Figure 5 for other loads than the rated load, the actual values of  $I_d$ ,  $d_{xt}$  and  $d_{xb}$  ~~have to~~ **shall** be taken to obtain the actual regulation  $d_L$  and from this the actual additional regulation  $U_{dL}$ .

That is:

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

is used to enter the diagram of Figure 5.

Figure 5 –  $d_{LN}$  as a function of  $d_{XN}$  for  $p = 6$  and  $p = 12$

NOTE The parameter for Figure 5 is:

$$\frac{1}{R_{1SC}} = \frac{S_{1LN}}{S_C} = \frac{U_{di} \times I_{dN}}{S_C}$$

#### 4.7.3.3 Measurement of the additional direct voltage regulation due to AC system impedance

A voltmeter on the DC side of the converter does not indicate the inherent voltage regulation (see 4.7.2) but a larger regulation.

The influence of the AC system impedance cannot be measured directly by a voltmeter indicating the RMS value on the AC voltage taken when the converter is on load.

The additional direct voltage regulation due to the AC system impedance can be measured with sufficient approximation by an appropriate measuring circuit using an auxiliary rectifier connected to the line side terminals of the converter, through a transformer if necessary.

This auxiliary rectifier have the same commutation number and pulse number as the converter and the ripple of its direct voltage have the same relative phase position to the AC network voltage as the ripple of the converter direct voltage.

The per unit change of the output voltage of the auxiliary rectifier during a change of the converter load represents the per unit change in the converter direct voltage due to the system impedance.

#### 4.7.3.4 Influence on direct voltage regulation of other converters connected to the same system

If other converters are fed from the same AC system, these may cause an additional voltage regulation of the converter under consideration even in the case of constant RMS value of AC voltage at converter terminals.

To enable the supplier to take such conditions into consideration, the purchaser should indicate prior to order the power, connection, location and other main particulars of the other converters.

#### 4.7.4 Information to be exchanged between supplier and purchaser about direct voltage regulation of the converter

To enable the supplier to calculate the effect of AC system impedance, the purchaser should give the AC system data before the order. When the system short-circuit power is given for this purpose, the value given should correspond to that configuration of the AC system for which the total voltage regulation is to be calculated.

The supplier should then indicate the following values:

- the inherent direct voltage regulation (see 4.7.2.6) of the converter

$$U_{dtN} + U_{dbN}$$

- the total voltage regulation of the converter, when the RMS value of the line side terminal voltage is kept constant

$$U_{dtN} + U_{dbN} + U_{dLN}$$

When values of system impedance are not given by the purchaser, the supplier should assume some specified finite value of the short-circuit power of the AC system or,

alternatively, should draw the purchaser's attention to Figure 5 by which the total voltage regulation can be calculated for any value of the AC system short-circuit power.

Sample calculations of voltage regulation are given in Clause 5.

#### 4.8 Voltage limits for reliable commutation in inverter mode

To prevent commutation failure or conduction-through, the design shall take into consideration the required maximum current, the highest direct voltage and the lowest AC system voltage which may occur simultaneously. Both steady-state and transient conditions have to be taken into consideration.

If not otherwise specified, the converter, when operating as an inverter, shall be able to carry all rated current values according to the duty class, without conduction-through at the rated minimum AC system voltage.

Under transient conditions such as in the case of voltage dips due to distant faults in the AC system, a commutation failure may occur particularly at maximum DC voltage in the inverter mode.

The following means may be used together or separately to reduce commutation failures or their consequences:

- lowering current limit setting;
- higher secondary voltage;
- lowering limit setting for rate of change of current;
- fast DC circuit-breaker or magnetic contactor, to operate particularly in the inverter mode;
- higher setting of the under-voltage relay (within rated limits);
- gate pulse train (instead of short gating signals);
- AC filter on the synchronizing input to the trigger equipment to prevent disturbances on the gating angle.

These means may not prevent all of the commutation failures but they would greatly reduce their number in most applications.

Automatic restarting after a tripping may be specified separately, but strict precautions shall be taken for the safety of the operators.

#### 4.9 AC voltage waveform

The deviation of line-to-neutral or line-to-line AC supply voltage from the instantaneous value of the fundamental wave (for example during commutation of power converters) may reach 0,2 p.u. or more of the existing crest value of the line voltage (Figure 6). Additional oscillations may appear at the beginning and at the end of each commutation.

Non-repetitive transients are mainly due to fault clearing and switching, as well as possible lightning strokes on overhead lines, which may have some effect on MV and LV systems.

The following values are given as examples only on the basis of the individual converter transformer characteristics and rating ( $S_{tN}$ ).

- a) Transient energy 400  $S_{tN}$  J

NOTE 1  $S_{tN}$  is expressed in MVA. The transient energy comes from the interruption of the transformer magnetizing current. The magnetizing current of the transformer is assumed to be 0,05 p.u. of its rated current.

- b) Rise time (0,1 to 0,9 peak value) 1  $\mu$ s

- c) Repetitive peak value ( $U_{LRM} / U_{LWM}$ ) 1,25 p.u.  
 d) Non-repetitive peak value ( $U_{LSM} / U_{LWM}$ ) 2,0 .. 2,5 p.u.

NOTE 2 The peak value is given assuming a typical suppressor is used. Without suppressor, this value could be 10 p.u. or more.

- e) Duration above 0,5 p.u. 3 .. 300  $\mu$ s

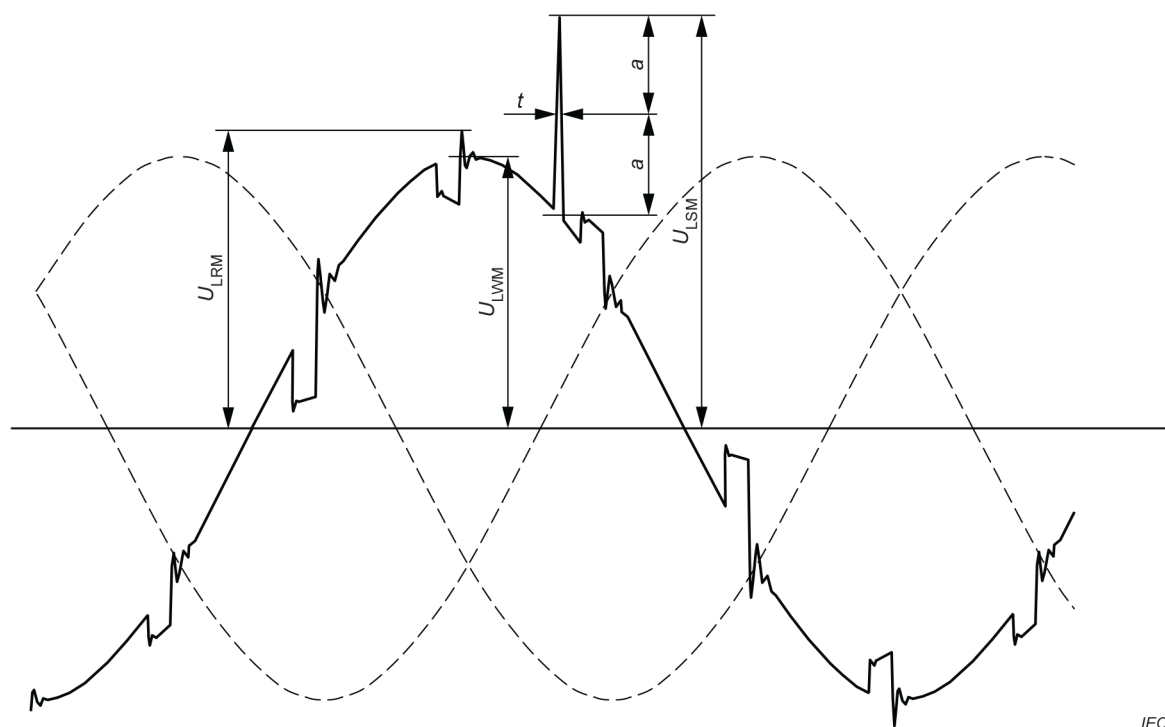
If several converters without individual transformers are connected to the same bus, the suppressor circuits shall be coordinated with the common transformer.

$U_{LRM}$  maximum instantaneous value of  $U_L$ , including repetitive over-voltages but excluding non-repetitive over-voltages

$U_{LSM}$  maximum instantaneous value of  $U_L$ , including non-repetitive over-voltages

$U_{LWM}$  maximum instantaneous value of  $U_L$ , excluding transient over-voltages

Figure 6 shows one non-repetitive transient with the amplitude  $U_{LSM}$  and the typical commutation notches of a 6-pulse power converter (connection No. 8, Table 1).



IEC

Figure 6 – AC voltage waveform

## 5 Application information

### 5.1 Practical calculation of the operating parameters

#### 5.1.1 General

If a project requires the calculations to be performed a number of times, as an alternative to using the figures and formulae in 4.6 and 4.7, it is expedient to use a computer or at least a programmable calculator.

The following formulae in 5.1.2 to 5.1.4 are sufficiently accurate for most cases, particularly for standard design converters.

For letter symbols, see 4.6.2 and IEC 60146-1-1:2009, 4.2.

### 5.1.2 Assumptions

The calculation implies that the following assumptions are valid:

- uniform connection;
- infinite smoothing inductance, i.e. negligible direct current ripple;
- pulse number  $p = 6$ ; commutation number  $q = 3$ ;
- negligible AC voltage unbalance;
- steady-state, i.e. constant direct voltage and current;
- angle of overlap  $\mu$  less than  $2\pi/p$ .

### 5.1.3 Preliminary calculations

~~The fundamental apparent power:~~

~~$$S_{1LN} = U_{di} \times I_{dN}$$~~

~~The inductive direct voltage regulation at rated direct current is:~~

~~$$U_{dxN} = \frac{\pi}{3} \times \frac{d_{xtN}}{e_{xtN}} \times \frac{S_{1LN}}{S_{com}} \times U_{di}$$~~

~~where~~

~~$$\frac{1}{S_{com}} = \frac{e_{xN}}{S_{tN}} + \frac{X_L}{U_{LN}^2} + \frac{1}{S_C}$$~~

~~$$X_L = 2\pi \times f_{1N} \times L$$~~

~~$S_C$  is the short-circuit power of the supply source;~~

~~$L$  is the cable or line inductance.~~

~~For six-pulse connection (see Table 1):~~

~~$$\frac{d_{xtN}}{e_{xN}} = 0,5$$~~

~~Inductive direct voltage regulation:~~

~~$$d_{xN} = \frac{\pi}{3} \times \frac{d_{xtN}}{e_{xN}} \times \frac{S_{1LN}}{S_{com}}$$~~

~~Resistive direct voltage regulation at rated current:~~

~~$$U_{drN} = \frac{P_{rN}}{I_{dN}}$$~~

~~where~~

~~$P_{rN}$  is the power losses in circuit resistance at rated load. The loss caused by threshold voltages of valve devices is excluded;~~

~~$d_{rN} = P_{rN}/(U_{di} \times I_{dN}) = P_{rN}/S_{1LN}$  (see NOTE 2 below of this subclause).~~

~~NOTE 1—The formula for  $d_{xtN}$  is derived as follows for  $U_v/U_{LN} = 1$  and assuming all a.c. inductances are merged in the transformer reactance  $X_{tN}$  giving  $S_{com}$ :~~

~~$$d_{xtN} = \frac{I'_L \times X_{tN} \times \sqrt{3}}{U_{LN}} \times \sin\left(\frac{\pi}{6}\right) \div I'_L = I_{dN} \times \sqrt{\frac{2}{3}} \div X_{tN} = \frac{U_{LN}^2}{S_{com}} \div \sin\left(\frac{\pi}{6}\right) = 0,5 \div U_{LN} = \frac{\pi \times U_{di}}{3\sqrt{2}}$$~~

~~hence:~~

~~$$d_{xtN} = 0,5 \times \frac{\pi}{3} \times \frac{U_{di} \times I_{dN}}{S_{com}} = 0,5 \times \frac{S_{LN}}{S_{com}}$$~~

~~NOTE 2—The transformer load losses may be expressed as:~~

~~$$e_{rN} \times S_{tN}$$~~

~~and the other losses are added giving:~~

~~$$d_{rN} = \frac{(e_{rN} \times S_{tN} + \text{other losses})}{S_{1LN}}$$~~

~~The equation is correct only if  $S_{tN}$  is based on the rated d.c. current  $I_{dN}$ .~~

The fundamental apparent power is calculated as follows:

$$S_{1LN} = U_{di} \times I_{dN}$$

The inductive voltage regulation including the effects from the reactances of the supply source and the feeder cable or line is calculated as below based on the first formula shown in 4.7.2.4.

$$d_{xtN} = \frac{\delta \times q \times s}{2 \times \pi \times g} \times X_{sum} \times \frac{I_{dN}}{U_{di}}$$

where

$X_{sum}$  =  $X_t + X'_L + X'_C$ , the sum of the reactances below:

$X_t$  is the commutation reactance of the converter transformer seen from the valve side;

$X'_L = \left(\frac{U_{V0}}{U_L}\right)^2 X_L$  is the reactance of the cable or the line seen from the valve side through the converter transformer;

$X'_C = \left(\frac{U_{V0}}{U_L}\right)^2 X_C$  is the reactance of the supply source seen from the valve side through the converter transformer.

The formula above for  $d_{xtN}$  can be derived considering that the commutation current flows from the supply source to the converter through the reactances between them. In other words, the commutation reactance is calculated from the sum of the reactances. In the calculation, the values of reactances at the line side should be converted to those seen from the valve side of the converter transformer since the voltage regulation is calculated based on the values of the valve side.

NOTE The calculations using the ratio ( $d_{xN} / e_{xN}$ ) in IEC 60146-1-2:2011 was removed and replaced with the equivalent and simple calculations. The equivalency is shown in Clause C.7.

Resistive direct voltage regulation at rated current:

$$U_{drN} = \frac{P_{rN}}{I_{dN}}$$

where

$P_{rN}$  is the power losses in circuit resistance at rated load. The loss caused by threshold voltages of valve devices is excluded.

$$d_{rN} = P_{rN} / (U_{di} \times I_{dN}) = P_{rN} / S_{1LN}$$

## 5.1.4 Calculation of the operating conditions

### 5.1.4.1 Direct voltage

With the assumptions of six-pulse uniform connection, the following formulae apply:

a) for rectifier:

$$U_{di} \times \cos \alpha = U_d + U_{TO} + (U_{drN} + U_{dxN}) \times \frac{I_d}{I_{dN}}$$

b) for inverter:

$$U_{di} \times \cos(\alpha + \mu) = U_d + U_{TO} + (U_{drN} - U_{dxN}) \times \frac{I_d}{I_{dN}}$$

where

$$U_{di} = U_{v0} \times 3\sqrt{2} / \pi;$$

$U_{TO}$  is the sum of threshold voltages of all valve devices connected in series in any current path;

$\frac{I_d}{I_{dN}}$  is the per unit direct current.

In the common case of a converter for a DC motor drive, the value of  $U_d$  is the DC motor counter e.m.f.  $E_d$  (proportional to shaft speed and motor flux) plus the armature voltage drop at rated current.

$$U_d = E_{dN} \times \frac{E_d}{E_{dN}} + R_a \times I_{dN} \times \frac{I_d}{I_{dN}}$$

In this case, the resistive voltage regulation  $U_{drN}$  includes all the voltage regulation caused by the losses except the loss caused by threshold voltage of the valve devices: resistance of the valve devices, armature, DC and AC cables, smoothing inductor, transformer windings.

In other cases,  $U_d$  is the converter voltage at its DC terminals and then  $U_{drN}$  does not include the losses in the DC circuits outside of the converter (cables and load or source).

$U_{dxN}$  includes all the voltage regulation caused by inductances in the AC circuit: transformer leakage reactance, line or anode reactance, cable reactance, supply system reactance, etc. (see 5.1.3).

**NOTE 1** In certain cases, not steady-state, the rate of current rise  $di/dt$  ~~has to~~ shall be provided for, by adding the term  $L di/dt$  to the converter DC voltage ( $L$  is the total inductance of the DC circuit).

**NOTE 2** In the case of a diode rectifier,  $\alpha = 0$ ,  $\cos \alpha = 1$ , the angle of overlap  $\mu$  is given by:

$$\cos \mu = 1 - 2 \times \frac{U_{dx}}{U_{di}}$$

The output voltage is given by:

$$U_d = U_{di} - (U_{dr} + U_{TO} + U_{dx})$$

#### 5.1.4.2 Displacement angle

The following approximation gives a satisfactory result in most cases:

$$\cos \varphi_1 = \frac{U_d + U_{TO} + U_{drN} \times I_d / I_{dN}}{U_{di}}$$

A more accurate formula is:

$$\tan \varphi_1 = \frac{2\mu + \sin 2\alpha - \sin[2(\alpha + \mu)]}{\cos 2\alpha - \cos[2(\alpha + \mu)]}$$

**NOTE** Radians are used in the latter formula.

#### 5.1.4.3 Rectifier and inverter operation

In rectifier operation, both current and voltage are considered as positive and also the active and reactive power.

In inverter operation, the current and reactive power are positive, the voltage and active power are negative.

As an example, Table 4 shows operating conditions and Table 5 shows operating points.

**Table 4 – Example of operating conditions**

|             | Value | Unit |
|-------------|-------|------|
| $E_{dN}$    | 450   | V    |
| $I_{dN}$    | 1812  | A    |
| $S_C$       | 115   | MVA  |
| $X_C / R_C$ | 8     | p.u. |
| $S_{tN}$    | 1,25  | MVA  |
| $e_{xN}$    | 0,055 | p.u. |
| $e_{rN}$    | 0,012 | p.u. |
| $U_{LN}$    | 400   | V    |
| $U_{TO}$    | 2,1   | V    |
| $R_a$       | 9,93  | mΩ   |

**Table 5 – Example of operating points**

|                  | Rectifying<br>steady-state | Starting | Inverting | Unit       |
|------------------|----------------------------|----------|-----------|------------|
| $I_d / I_{dN}$   | 1,03                       | 1,6      | 1,175     | p.u.       |
| $E_d / E_{dN}$   | 1,055                      | 0,0      | -0,288    | p.u.       |
| $U_{di}$         | 540                        | 540      | 540       | V          |
| $U_{dx}$         | 15,0                       | 23,3     | 17,1      | V          |
| $U_{dr}$         | 5,2                        | 8,1      | 5,96      | V          |
| $\alpha$         | 23,2                       | 83,4     | 98,3      | ° (degree) |
| $\mu$            | 5,2                        | 4,97     | 3,7       | ° (degree) |
| $\cos \varphi_1$ | 0,892                      | 0,072    | -0,176    | –          |
| $\varphi_1$      | 26,9                       | 85,9     | 93,3      | ° (degree) |
| $S_{1L}$         | 1,01                       | 1,57     | 1,15      | MVA        |
| $P_L / P_{1L}$   | 0,899                      | 0,113    | -0,213    | MW         |
| $Q_{1L}$         | 0,455                      | 1,56     | 1,13      | Mvar       |

## 5.2 Supply system voltage change due to converter loads

### 5.2.1 Fundamental voltage change

The voltage change may be estimated using the formula:

$$\frac{\Delta U}{U} \approx \frac{S_{1L}}{S_C} \times \cos \left[ \tan^{-1} \left( \frac{X_C}{R_C} \right) - \varphi_1 \right]$$

where

$X_C$  is the reactance of the supply source;

$R_C$  is the resistance of the supply source.

NOTE  $X_C / R_C$  may vary from 4 p.u. to 10 p.u.

### 5.2.2 Minimum $R_{1SC}$ requirements for voltage change

The ratio of the short-circuit power of the supply source to the fundamental apparent power of the converter is:

$$R_{1SC} = \frac{S_C}{S_{1LN}}$$

The minimum  $R_{1SC}$  as regards the voltage regulation between no-load and peak load is:

$$R_{1SCmin} = \frac{S_{Cmin}}{S_{1Lm}} = \frac{\cos \left[ \tan^{-1} \left( \frac{X_C}{R_C} \right) - \varphi_{1m} \right]}{\left( \frac{\Delta U_L}{U_L} \right)_m}$$

where

$$S_{1Lm} = U_{di} \times I_{dMN};$$

$I_{dMN}$  is the rated continuous direct current (maximum value).

#### EXAMPLE

Assume:  $X_C / R_C = 10$ ; then  $\tan^{-1}(X_C / R_C) = 84,29^\circ$

Assume:  $\cos \varphi_{1m} = 0,1$ ; then  $\varphi_{1m} = 84,26^\circ$

Hence:  $\cos[\tan^{-1}(X_C / R_C) - \varphi_{1m}] \approx 1,0$

If:  $(\Delta U_L / U_L)_m = 0,08$

then:  $R_{1SCmin} \approx 1,0 / 0,08 = 12,5$

### 5.2.3 Converter transformer ratio

The actual system voltage change may be approximated in two or more iteration steps.

In the first iteration,  $P_1$ ,  $Q_1$ ,  $\varphi_1$  are calculated using the estimated secondary voltage corresponding to the on-load system voltage.

The voltage is then corrected to calculate the new values of  $P_1$ ,  $Q_1$ ,  $\varphi_1$ ,  $\Delta U_L / U_L$ :

$$U_{L(n+1)} = U_{LN} \times \left[ 1 - \left( \frac{\Delta U_L}{U_L} \right)_n \right]$$

The new voltage change may be used for further iterations in order to optimize the transformer ratio and rating. However, other criteria may have to be considered such as the voltage changes due to other causes.

As an example of calculation, operating conditions shown in Table 6 is considered. The result of the iteration is shown in Table 7.

**Table 6 – Example of operating conditions**

| Rated values                                                                    |              | Value   | Unit     |
|---------------------------------------------------------------------------------|--------------|---------|----------|
| DC voltage                                                                      | $U_{dN}$     | 5 000   | V        |
| DC current                                                                      | $I_{dN}$     | 2 200   | A        |
| DC circuit resistance                                                           | $R_a$        | 0,136   | $\Omega$ |
| Transformer rating                                                              | $S_{tN}$     | 15      | MVA      |
| <b>Short-circuit voltage</b>                                                    |              |         |          |
| Inductive component                                                             | $e_{xN} e_x$ | 0,085   | p.u.     |
| Resistive component                                                             | $e_{rN}$     | 0,008 7 | p.u.     |
| Secondary voltage                                                               | $U_{LN}$     | 5 080   | V        |
| Valve device threshold voltage drop                                             | $U_{TO}$     | 38      | V        |
| Supply source short-circuit power<br>( $e_{xN}$ and $e_{rN}$ include AC cables) | $S_C$        | 150     | MVA      |