

INTERNATIONAL STANDARD

NORME INTERNATIONALE



**Converter transformers –
Part 1: Transformers for industrial applications**

**Transformateurs de conversion -
Partie 1: Transformateurs pour applications industrielles**



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INTERNATIONAL STANDARD

NORME INTERNATIONALE



**Converter transformers –
Part 1: Transformers for industrial applications**

**Transformateurs de conversion -
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COMMISSION

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CONVERTER TRANSFORMERS –**Part 1: Transformers for industrial applications**

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International Standard IEC 61378-1 has been prepared by IEC technical committee 14: Power transformers.

This bilingual version (2014-07) corresponds to the English version, published in 2011-07.

This second edition cancels and replaces the first edition published in 1997. It constitutes a technical revision.

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

- addition of winding connections (zig-zag, extended delta, etc.) with phase displacement ($< 30^\circ$);
- addition of transformers with more than one active part in the same tank;
- change of reference power definition (it is now based on fundamental component of the current);

- addition of considerations for guidelines for OLTC selection;
- addition of regulating transformer feeding converter transformer;
- addition of considerations about current sharing and hot spot temperature in high current windings for various winding arrangements;
- addition of transducers used for d.c. voltage regulation together with diode rectifiers;
- improved old annexes with several calculation examples;
- addition of new annexes for special measurements setups.

The text of this standard is based on the following documents:

FDIS	Report on voting
14/686/FDIS	14/695/RVD

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

The French version of this standard has not been voted upon.

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

A list of all parts of the IEC 61378 series can be found, under the general title *Converter transformers*, on the IEC website.

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

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

The contents of the corrigendum of January 2012 have been included in this copy.

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CONVERTER TRANSFORMERS –

Part 1: Transformers for industrial applications

1 Scope

This Part of IEC 61378 deals with the specification, design and testing of power transformers and reactors which are intended for integration within semiconductor converter plants; it is not applicable to transformers designed for industrial or public distribution of a.c. power in general.

The scope of this International Standard is limited to application of power converters of any power rating. Typical applications are: thyristor rectifiers for electrolysis; diode rectifiers for electrolysis; thyristor rectifiers for large drives; thyristor rectifiers for scrap melting furnaces, and diode rectifiers feeding inverters for variable speed drives. The standard also covers the regulating unit utilized in such application as step down regulating transformers or autotransformers. The valve winding highest voltage for equipment is limited to 36 kV.

This standard is not applicable to transformers for HVDC power transmission. These are high-voltage transformers, and they are subjected to d.c. voltage tests.

The standards for the complete converter plant (IEC 60146 series, or other publications dedicated to particular fields of application) may contain requirements of guarantees and tests (such as insulation and power loss) for the whole plant, including the converter transformer and possibly auxiliary transformers and reactor equipment. This does not relieve the application of the requirements of this standard concerning the guarantees and tests applicable to the converter transformer itself as a separate component before being assembled with the remainder of the converter plant.

The guarantees, service and type tests defined in this standard apply equally to transformers supplied as part of an overall converter package, or to those transformers ordered separately but for use with converter equipment. Any supplementary guarantee or special verification has to be specifically agreed in the transformer contract.

The converter transformers covered by this standard may be of the oil-immersed or dry-type design. Unless specific exceptions are stated in this standard, the transformers comply with IEC 60076 series for oil-immersed transformers, and with IEC 60076-11 for dry-type transformers.

NOTE For some converter applications, it is possible to use common distribution transformers of standard design. The use of such standard transformers in the special converter applications may require a certain derating. This matter is not specifically covered in this standard, which deals with the requirements to be placed on specially designed units. It is possible to estimate this derating from the formulae given in 5.1, and also from Clause 9 of IEC 60076-8:1997.

This standard deals with transformers with one or more active parts installed in the same tank like regulating (auto)transformer and one or two rectifier transformers. It also covers transformers with transducers and/or one or more interphase transformers.

For any combination not listed above an agreement between the purchaser and manufacturer is necessary regarding the determination and the measurement of the total losses.

This standard deals with transformers star Y and delta D and any other phase shifting connections (like zig-zag, extended delta, polygon etc.). Phase shifting windings can be placed on either the regulating or rectifier transformer.

2 Normative references

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

IEC 60050-421:1990, *International Electrotechnical Vocabulary (IEV) – Chapter 421: Power transformers and reactors*

IEC 60076 (all parts), *Power transformers*

IEC 60076-1:2011, *Power transformers – Part 1: General*

IEC 60076-2:2011, *Power transformers – Part 2: Temperature rise for liquid-immersed transformers*

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

IEC 60076-6:2007, *Power transformers – Part 6: Reactors*

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

IEC 60076-11:2004, *Power transformers – Part 11: Dry-type transformers*

IEC 60146 (all parts), *Semiconductor converters – General requirements and line commutated converters*

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

IEC/TR 60146-1-2:2011, *Semiconductor converters – General requirements and line commutated converters – Part 1-2: Application guide*

IEC/TR 60616:1978, *Terminal and tapping markings for power transformers*

3 Terms, definitions and acronyms

3.1 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 60050-421, IEC 60076-1 and IEC 60146-1-1, as well as the following apply.

3.1.1

polygon connection

P

the winding connection in which each phase winding consists of two parts in which phase displaced voltages are induced. One part of each phase is connected in series to the other part of a different phase and then closed in a delta (see Annex I)

3.1.2

extended delta connection

E

the winding connection in which each phase winding consists of two parts in which phase displaced voltages are induced. One part of each phase is delta connected and it is then connected to its appropriate line terminal through the other part (see Annex I)

3.1.3

phase shifting angle

Γ

the angle with sign, expressed in degrees and decimal of degrees, which needs to be added to the nearest clock number to obtain the phase displacement

3.1.4

transductor

device consisting of one or more ferromagnetic cores with windings, by means of which an a.c. or d.c. current or voltage can be varied by an independent voltage or current, utilizing saturation phenomena in the magnetic circuit

NOTE The French term transducteur magnétique (English: transductor) should not be confused with the more general French term transducteur (English: transducer). The use of the term transducteur in the sense of transducteur magnétique is permissible when no ambiguity is possible.

[IEC 60050-431:1980, 431-01-01]

3.1.5

interphase transformer

an electromagnetic device enabling the operation in parallel of two or more phase displaced commutating groups through inductive coupling between the windings placed on the same core [IEC 60050-551:1998, 551-14-16]

3.1.6

line side

transformer winding connected to the a.c. network

3.1.7

valve side

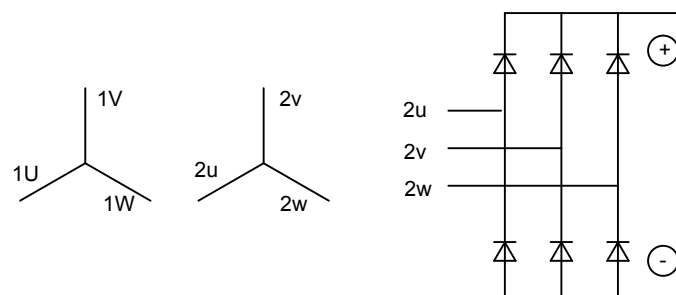
transformer winding connected to the converter

3.2 Acronyms

B6U 6-pulse double bridge connection (see Figure 1 below)

DB double bridge connection (see Figure 1 below)

NOTE The transformer windings can be star or delta connected.



IEC 1720/11

Figure 1 – B6U or DB 6 pulse double bridge connection

DSS double star with interphase transformer (see Figure 2 below)

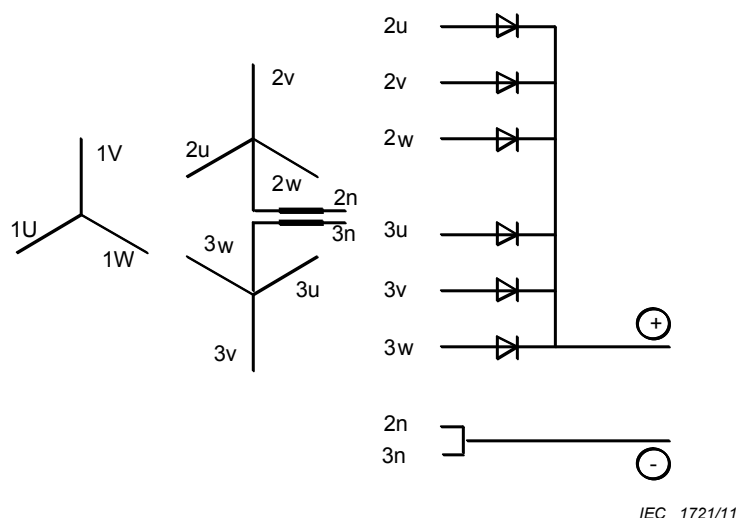


Figure 2 – DSS 6 pulse connection

IPT see definition 3.1.5
 SR see definition 3.1.4
 FFT fast fourier transformation

4 Classification

4.1 General

Classification of converters and converter applications are given in 4.1 of IEC 60146-1-1:2009 and in 4.1 of IEC/TR 60146-1-2:2011. From the aspect of transformer design, it is important to distinguish between

- applications with essentially sinusoidal voltage across the transformer, and
- applications with non-sinusoidal voltage where the transformer primary is energized from a converter circuit for a.c. power control or variable frequency conversion.

It is also important to distinguish between

- applications characterized by a continuous load, such as electrolysis, d.c. arc furnace etc., and
- applications with short-time cyclic or irregular load variation, such as reversible mill-motor drives, etc.

Information about the converter application should be supplied in the transformer specification. This is detailed further in following subclauses of this standard.

4.2 Normal service conditions

Normal service conditions for the transformer are in accordance with IEC 60076-1, IEC 60076-2, IEC 60076-11 and IEC 60146-1-1.

Any deviation of the a.c. voltage from the rated voltage value or tapping voltage value, sinusoidal wave shape or three-phase symmetry should be within the limits of immunity class B, according to 5.4 of IEC 60146-1-1:2009. If the converter transformer is supplied with non-sinusoidal voltage, inverter or frequency converter application, it is necessary that information on the range of variation of service voltage shape and frequency variation shall be submitted in

the specification. It is also important that information is given regarding the d.c. component of the applied voltage cycle.

4.3 Provision for unusual service conditions

In addition to the unusual service conditions to be specified for power transformers, in case of transformers with more than two windings, each loading combination of the windings is to be clearly specified. Each loading combination shall include the respective current harmonic components.

Examples of this type of unusual service conditions are no or reduced load on tertiary compensation winding or on one valve winding.

5 Ratings

5.1 General

IEC 60076-1 applies, with the following additions and explanations.

Transformers for converter application are loaded with non-sinusoidal current, and sometimes work with non-sinusoidal voltage. Even the frequency may vary considerably in certain applications.

The rating of the transformers on which the tests will be conducted and to which the corresponding guarantees are related is expressed in sinusoidal quantities of fundamental frequency in steady state.

The following subclauses provide guidance as to how to determine the transformer rating when the details of the converter and other information about the loading are available.

5.2 Rated power at rated frequency and load capability

The rated power of the converter transformer line side winding is based on the fundamental frequency components of voltage and current, hence the rated three-phase power is:

$$S_R = \sqrt{3} \times U_1 \times I_1 \quad (1)$$

where

U_1 is the r.m.s. value of the fundamental component of the line-to-line voltage;

I_1 is the r.m.s. value of the fundamental component of the rated line side current. This fundamental component is calculated from an ideal rectangular waveshape current (see Table 1).

The rated power S_R and line current I_1 shall be used for guaranteed load losses and short circuit impedance.

The rated power of the valve windings S_V is equal to the rated power of the line winding multiplied by a factor which is a function of number of valve windings and type of rectifier (single or double way). This factor is defined in Table 1.

The thermal design and cooling system of the transformers shall be determined after allowance is made for the increased losses due to harmonics (including d.c. components) by means of an equivalent thermal current to be used in temperature rise test (see Clause 6).

In case of cyclic loading, the load variation pattern shall be included by the purchaser in the transformer specification.

5.3 Rated and service voltages

5.3.1 Transformer energized from an a.c. power system

For a converter transformer connected to an a.c. power system, the rated voltage shall be as specified in 5.4 of IEC 60076-1:2011 and in IEC 60076-8.

5.3.2 Transformer energized from a converter/inverter with or without variable frequency

For a converter application with a considerably distorted transformer voltage, the rated voltage shall be the r.m.s. value of the sinusoidal fundamental component derived from the Fourier series analysis of the maximum continuous service voltage.

For applications with such a distorted transformer voltage, or with variable frequency, information shall be given in the specification concerning the applied voltage under various service conditions.

NOTE For the above applications, the amplitude of flux density in the magnetic circuit is the determining parameter, and not the amplitude of a non-sinusoidal voltage. The value of flux is determined by the voltage-time integral over a half-cycle. This value will be the maximum value in continuous service. If short-time higher values of the voltage-time integral exist, they should also be included in the specification, to permit checking against possible overfluxing.

5.4 Rated current

The rated current of the transformer is the r.m.s. value of the fundamental component of current corresponding to rated power according to 5.2.

5.5 Phase displacement and terminal identification for three-phase transformer

The definition of phase displacement is described in 3.10.6 of IEC 60076-1:2011.

Whenever the 'clock number' notation outlined in the Clause 7 of IEC 60076-1:2011 is not sufficient to identify the phase displacement; the nearest clock number shall be used followed by the value with sign of the angle Γ which has to be added to obtain the exact phase displacement. The indication of the sign of the Γ has to follow the definition of the leading and lagging displacement included in 3.10.6 of IEC 60076-1:2011 (see Annex I).

The terminal identification of a converter transformer shall also include the information regarding the sequence of the commutating valve. Therefore the terminals are expressed by a code of three symbols as described below.

<i>First symbol:</i>	Number, that refers the different winding systems (with 1 for line side winding).
<i>Second symbol:</i>	Letter, that refers the sequence of the phases according to the IEC 60616.
<i>Third symbol (optional):</i>	"+" or "-" that refers to which polarity of the rectifier the terminal is connected to.

Examples of different type of connections, phase displacement and terminal indications are included in the Annex I.

If the phase displacement changes with tap position, the one on the nominal tap shall be indicated and the range of variation shall be agreed at the tender stage.

5.6 Rating plate

In addition to the information normally provided for power transformers, the following data shall be included in the rating plate:

- connection and phasor diagram with indication of angular displacement (as per 5.5);
 - eddy loss enhancement factor;
 - r.m.s. value of the load current (which includes fundamental and harmonics);
- NOTE In case of a power transformer loaded with pure sinusoidal current the eddy loss enhancement factor would be equal to 1 and the r.m.s. load current is equal to the rated current.
- type of rectifier to which the transformer will be connected (single/double way, diodes, thyristors);
 - cooling characteristics, if water cooled, water flow rate, inlet pressure and pressure drop in the cooling equipment;
 - in case of regulating (auto)transformer and rectifier transformer(s) in the same tank, the primary voltage of the rectifier transformer.

In case transducers are present, then the following information shall be supplied:

- number of turns of bias, control and test (if present) windings;
- rated current of bias, control and test (if present) windings;
- d.c. voltage drop;
- connection diagram of the bias, control and test (if present) windings with terminal identification.

5.7 Units with tertiary windings loaded with filter and compensation

A tertiary winding on the transformer may be requested for power factor compensation and harmonic filtering purposes.

In addition to specifying the rated power and voltage of the tertiary winding, the purchaser shall specify the combinations of transformer loading conditions. This concerns:

- primary supply voltage, including variation limit;
- secondary side: voltage, power factor and current (fundamental and harmonics);
- tertiary side: voltage, power factor and current (fundamental and harmonics).

The rated current of the tertiary winding is defined as the rms value in ampere of the fundamental component of the current at rated tertiary voltage (I_{rated} = fundamental component of $I = U_{\text{rated}} / Z$, where Z is the impedance of the compensation / filtering bank).

Current harmonics caused by line voltage harmonics flow to the filters. A resonance might occur by the transformer and the network reactance and the compensation capacitor. In this case, large harmonic current flows to the capacitor. The purchaser shall consider the network condition and specify harmonics accordingly.

The following conditions shall be taken into account, if specified by the purchaser, when designing the transformer:

- when overfluxing occurs, the power supplied by the tertiary winding varies with the square value of the voltage;
- because the power factor compensation has the effect of decreasing the supplied power, the purchaser shall specify whether the primary winding shall be designed for the power when the compensation capacitor bank is disconnected;

- depending on the winding arrangement overfluxing may occur at reduced or no load on the secondary winding while the tertiary winding remains connected to the compensation capacitor.

NOTE These information are a result of an interactive process and may change during project development.

5.8 On load tap-changers

The breaking capacity of an on-load tap-changer depends on the maximum slope of the current after it crosses zero value. For converter industrial applications, this value differs from the one found in applications for power transformers (as described in IEC 60076-1) and is essential for the proper selection of the on-load tap-changer. This value, expressed in A/s, shall be provided to the transformer manufacturer by the purchaser.

6 Load loss and voltage drop in transformers and reactors

6.1 General

The measurement of load loss shall be carried out with the rated current. The comparison with the guaranteed load losses defined before manufacturing shall be based on this measurement.

The actual load loss in service includes additional loss due to distorted current. This value shall be calculated in accordance with the procedure of 6.2. It is not guaranteed, but shall be provided by the transformer manufacturer for the purchaser.

The actual load loss, calculated as above, shall be used as the base for determining the oil and winding temperature rises, and to verify that they do not exceed the values permitted in IEC 60076-2 for oil-immersed transformers and IEC 60076-11 for dry-type transformers.

The temperature-rise type test on the transformer, when specified, shall be conducted with allowance for service load loss (see 5.1 and 7.6).

6.2 Determination of transformer load loss under distorted current loading

The load loss in a transformer is conventionally subdivided into loss as measured with d.c. (I^2R loss) and, in addition, eddy loss in windings and connections and stray losses in conductive structural parts of the transformer.

For transformers with low-voltage high-current windings, in the range of a few kA, the internal high current connections require a separate analysis of the additional eddy loss. The following principles are used in this standard:

- winding connections and metallic shields of high conductivity such as copper or aluminium are linear elements. Their eddy losses are proportional to the square of the current:

$$P(I) = \text{constant} \times I^2 \quad (2)$$

- a similar relationship is also valid for shields of magnetic core steel, when used in unsaturated conditions:

$$P(B) = \text{constant} \times B^2 \quad (3)$$

where B is the flux density in the magnetic shield;

- for the stray losses in structural steel parts, a square law relationship may also be used with reasonable accuracy:

$$P(B) = \text{constant} \times B^2 \quad (4)$$

where $B^2 = \text{constant} \times I^2$.

In normal service, the converter transformer load current is non-sinusoidal. When transformed into a Fourier series, it shows a number of harmonic currents of considerable size. These harmonic currents cause eddy loss and stray flux loss, and significantly increase the total loss calculated or measured with pure sinusoidal current.

A correction to the higher loss value at rated, non-sinusoidal converter load is required for the thermal dimensioning of the transformer, and for the correct calculation of the loss and efficiency of the complete converter installation. The harmonic components shall be specified or approved by the purchaser prior to the time of placing the order. The harmonic components shall list the r.m.s. value in ampere and phase in degrees of each harmonic for each of the transformer windings connected to terminals.

The transformer manufacturer does not have the necessary information and knowledge to predict the current harmonic generated by the converter. The purchaser has the responsibility of specifying the harmonics to which the transformer will be subjected, whilst the transformer manufacturer has the responsibility of designing the transformer taking into account the specified harmonics.

The purchaser shall specify or approve the harmonic components of the current at rated load prior to the time of placing the order. In the past, in absence of specific information, the harmonic components could be derived according to 5.5 of IEC/TR 60146-1-2:2011. However, current developments in electronics make possible the application of real-time control techniques that significantly alter the behaviour of the converter. The result is that a clear relationship between the converter power circuit configuration and its number of pulses, and hence the value of the current harmonics, is uncertain and the actual current harmonics may differ significantly from those computed according to 5.5 of IEC/TR 60146-1-2.

In any case the current harmonic components to be used for the design of the transformer shall be clearly defined and communicated by purchaser to the transformer manufacturer prior to the time of placing the order. It is the responsibility of the purchaser to decide whether harmonic components derived according to 5.5 of IEC/TR 60146-1-2 or any harmonic components proposed by the transformer manufacturer is acceptable.

The following rules are given for the recalculation of the measured loss under test to the loss value valid under the specified converter loading.

List of variables and relationships between them:

I_L	is the r.m.s. value of non-sinusoidal line current of the transformer;
I_{LN}	is I_L at rated converter load;
I_{PN}	is the r.m.s. value of the non-sinusoidal primary phase current at rated load;
I_{SN}	is the r.m.s. value of the non-sinusoidal secondary phase current at rated load;
I_{PT}	is the r.m.s. value of the primary phase current during load loss tests (first approximation for the injection of the total load loss);
I_{ST}	is the r.m.s. value of the secondary phase current (six phases) during load loss tests;
I_{WN}	is the r.m.s. value of the rated current in the winding under test;
I_h	is the r.m.s. value of harmonic current, having order number h ;
I_P	is a sinusoidal primary phase current having a r.m.s. value equal to I_{PN} ;
I_S	is a sinusoidal secondary phase current having a r.m.s. value equal to I_{SN} ;
I_1	is the r.m.s. value of the fundamental current, at rated load (that is equal to transformer rated current);
I_{1P}	is the r.m.s. value of the transformer fundamental primary phase current;
I_{1S}	is the r.m.s. value of the transformer fundamental secondary phase current;

I_{eq}	is the r.m.s. value of the equivalent sinusoidal test current for the determination of winding temperature rise;
I_{dN}	is the rated direct current;
I_{1v}	is the r.m.s. value of the fundamental component of the valve current;
I_{0v}	is the d.c. component value of the valve current;
U_{d0}	is the conventional no-load direct voltage (see IEC 60050-551:1998, 551-17-17);
U_{di}	ideal no load direct voltage;
U_{v0}	no load line to line voltage on the line side of the converter or on the valve side of the transformer;
h	is the harmonic order number;
P_0	is the no-load loss at rated voltage;
P_N	is the transformer load loss with current I_{LN} ;
P_1	is the transformer load loss with current I_1 ;
P_W	is the winding loss with current I_L ;
P_{Wh}	is the winding loss with current I_h ;
P_{W1}	is the winding loss with current I_1 ;
P_{WP}	is the primary winding loss with current I_{LN} ;
P_{WS}	is the total secondary winding and associated busbar loss with current I_{LN} ;
P_{WE}	is the winding eddy loss with current I_L ;
P_{WEh}	is the winding eddy loss with current I_h ;
P_{WE1}	is the winding eddy loss with current I_1 ;
P_{WE1h}	is the winding eddy loss with current I_1 , fundamental frequency and leakage field shape identical to the one produced by current I_h ;
P_C	is the connection loss with current I_L ;
P_{Ch}	is the connection loss with current I_h ;
P_{C1}	is the connection loss with current I_1 ;
P_{CE}	is the connection eddy loss with current I_L ;
P_{CEh}	is the connection eddy loss with current I_h ;
P_{CE1}	is the connection eddy loss with current I_1 ;
P_{SE}	is the structural parts stray loss with current I_L ;
P_{SE1}	is the structural parts stray loss with current I_1 ;
$P_A, P_{A1}, P_{A2}, P_B, P_{B1}, P_{B2}, P_C$	are the short-circuit losses measured under valve side terminals short-circuit conditions A, A1, A2, B, B1, B2 and C referred in Table 1;
$e_{XA}, e_{XA1}, e_{XA2}, e_{XB}, e_{XB1}, e_{XB2}, e_{XC}$	are the short-circuit impedances measured under valve side terminals short-circuit conditions A, A1, A2, B, B1, B2 and C referred in Table 1;
R_W	is the d.c. resistance of windings;
R_C	is the d.c. resistance of connections;
F_{WE}	is the eddy loss enhancement factor for windings (see Annex A);
F_{CE}	is the eddy loss enhancement factor for connections (see Annex A);
F_{SE}	is the stray loss enhancement factor for structural parts (see Annex A);
K_{WE}	is the windings enhancement loss p.u. at fundamental frequency due to eddy losses (see Annex A);
S_V	is the rated power of the valve windings. Its value is the result of the multiplication of S_R by the power ratio found in Table 1;

- S_R is the rated power of the converter transformer line side winding. It is based on the fundamental components of voltage and current;
- x is the exponent to be applied on the frequency harmonic order in calculations of eddy and stray loss enhancement.

$$I_L^2 = \sum_1^n I_h^2 \quad (5)$$

$$P_{WE} = \sum_1^n P_{WEh} = F_{WE} \times P_{WE1} = P_W - R_W \times I_L^2 \quad (6)$$

where R_W is seen from the line side.

$$P_{WE1} = P_{W1} - R_W \times I_1^2 \quad (7)$$

$$P_{WEh} = P_{WE1} \times \left(\frac{I_h}{I_1} \right)^2 \times h^2 \times \left(\frac{P_{WE1h}}{P_{WE1}} \right) \quad (8)$$

where for harmonic number h , $\left(\frac{P_{WE1h}}{P_{WE1}} \right)$ is a coefficient function of geometrical arrangement and coupling between windings. Its value varies from 0 to some decimals over 1. It equals 1 when current I_h produces a magnetic leakage field with the same shape of the one produced by current I_1 . See 6.4, Figures 3 to 6 and Annex A, Examples A.3 to A.6 for more information.

$$F_{WE} = \sum_1^n \left(\frac{I_h}{I_1} \right)^2 \times h^2 \times \left(\frac{P_{WE1h}}{P_{WE1}} \right) \quad (9)$$

$$P_{CE} = \sum_1^n P_{CEh} = F_{CE} \times P_{CE1} = P_C - R_C \times I_L^2 \quad (10)$$

where R_C is seen from the line side.

$$P_{CE1} = P_{C1} - R_C \times I_1^2 \quad (11)$$

$$F_{CE} = \sum_1^n \left(\frac{I_h}{I_1} \right)^2 \times h^{0.8} \quad (12)$$

R_C mainly originates in valve winding connection and the harmonic spectrum to take into account is the valve winding one. When the busbars are well compensated harmonics offsetting each other will be omitted.

$$P_{SE} = F_{SE} \times P_{SE1} \quad \text{and} \quad F_{SE} = F_{CE} \quad (13)$$

The stray losses in structural parts can be divided in a) the stray flux produced by the currents in the valve winding busbars and b) the stray flux produced by the currents in the windings. To use $F_{SE} = F_{CE}$ is an acceptable simplification by excess.

$$K_{WE} = \frac{P_{WE1}}{R_W \times I_1^2} \text{ (per unit)} \quad (14)$$

The load loss at rated current, I_1 of the transformer is subdivided into the following terms:

- i) $I_1^2 R$ = d.c. loss in windings and connections based on measured R_W and R_C ;
- ii) eddy loss in windings, P_{WE1} (calculated);
- iii) eddy loss in high-current busbars, when present, P_{CE1} (derived);
- iv) stray loss induced in structural steel parts, P_{SE1} (derived).

The sum of $P_{CE1} + P_{SE1}$ is the remainder when the previous terms from i) and ii) have been subtracted from the measured total loss.

The following relations apply:

$$P_1 = I_1^2 \times (R_W + R_C) + P_{WE1} + P_{CE1} + P_{SE1} \quad (15)$$

$$\begin{aligned} P_N &= I_{LN}^2 \times (R_W + R_C) + P_{WE} + P_{CE} + P_{SE} \\ &= I_{LN}^2 \times (R_W + R_C) + F_{WE} \times P_{WE1} + F_{CE} \times P_{CE1} + F_{SE} \times P_{SE1} \end{aligned}$$

NOTE 1 The sum $P_{CE1} + P_{SE1}$ is uprated with a common enhancement factor $F_{CE} = F_{SE}$ to obtain the losses at rated non-sinusoidal converter load.

NOTE 2 Different windings of a converter transformer may have different values of rated power and also different proportions of $I^2 R$ and eddy loss. The respective components in the equation above should therefore be interpreted as the sum of values calculated for each winding separately.

NOTE 3 Resistance measurements, especially when the secondary voltage is low and the secondary current is high, may lead to inaccuracies, because of

- a) difficulties in measuring low resistances;
- b) the influence of the short-circuiting device.

In case of multiple active parts in the same tank, the quantities above shall be computed for each active part with the current harmonics specific to that part.

6.3 Current sharing, losses and hot spot in high current windings

Valve windings in converter transformers for industrial applications are often characterized by a small number of turns and large rated currents (from several kA and more). Often the consequence of this fact is that the valve winding has to be made of several coils connected in parallel.

Whenever a winding is made up of coils connected in parallel, the sharing of the total winding current among the coils will be influenced by the self and mutual reactance of each coil and by the loading of other windings. In general, coils exposed to radial leakage flux will carry a higher current than the coils exposed to axial leakage flux only.

Typical current values for coils placed at the ends of a valve winding can be 1,2 to 1,7 times the value of current corresponding to a perfectly even sharing among coils. In addition, it shall be noted that also the current sharing between the strands forming the turns of these higher loaded coils is unequal unless even current sharing among the strands is achieved by perfect transposition or by using continuously transposed cable.

This means that these windings will exhibit a difference between hot spot and average temperature rise which can be significantly higher than that of other windings.

Therefore a simple hot spot factor cannot be assumed and load losses need to be computed accurately. In particular the manufacturer shall compute:

- a) I^2R loss due to uneven current sharing among the coils making up the high current winding;
- b) I^2R due to uneven current sharing among the strands making up the turns of each coil;
- c) eddy loss in each strand making up the turns of each coil.

These calculations can be carried out by means of magnetic field simulations which take into account both the connections among the different coils and windings in the transformer and sinusoidal variation of currents versus time.

There is a need for one simulation for each leakage field pattern (see following subclause).

6.4 Effect of geometrical winding arrangement and magnetic coupling between windings on their eddy current losses due to harmonics in transformers with three or more windings wound on the same core limb

In a two-winding transformer, ampere-turns are balanced if we neglect the magnetizing current. The harmonic currents flowing in the valve winding are balanced by harmonics (with the same p.u. magnitude) in the line winding; therefore the eddy loss enhancement factor is the same for both the line and valve windings.

In a transformer with three windings it is known that the sum of all windings ampere-turns adds up to zero and so it is necessary to consider in detail how to calculate each winding eddy-loss enhancement factor.

It is possible to identify the following configurations for three winding core-type transformers characterized by the coupling between valve windings:

- a) close coupling – two-valve windings interleaved and one line winding;
- b) no coupling – two pairs of valve-line windings separated by an intermediate yoke or belonging to two separate cores;
- c) loose coupling –
 - i) double concentric transformer with one line winding positioned radially between the two valve windings;
 - ii) two line windings in parallel, one above the other, each line winding facing one valve winding.

After measuring current harmonics at all three transformer terminals, it is possible to observe that, while some harmonics injected into the valve windings appear on the line with an identical p.u. value, other harmonics are not present on the line side.

Therefore, it is possible to divide the harmonics injected into the valve windings into two groups:

- 1) harmonics in phase – there is no phase displacement between these harmonics flowing in the valve windings; they sum and appear on the line side;
- 2) harmonics in phase opposition – there is a 180° phase displacement between these harmonics flowing in the valve windings; they cancel and do not appear on the line side¹.

Harmonic currents in phase always contribute to the total eddy loss value.

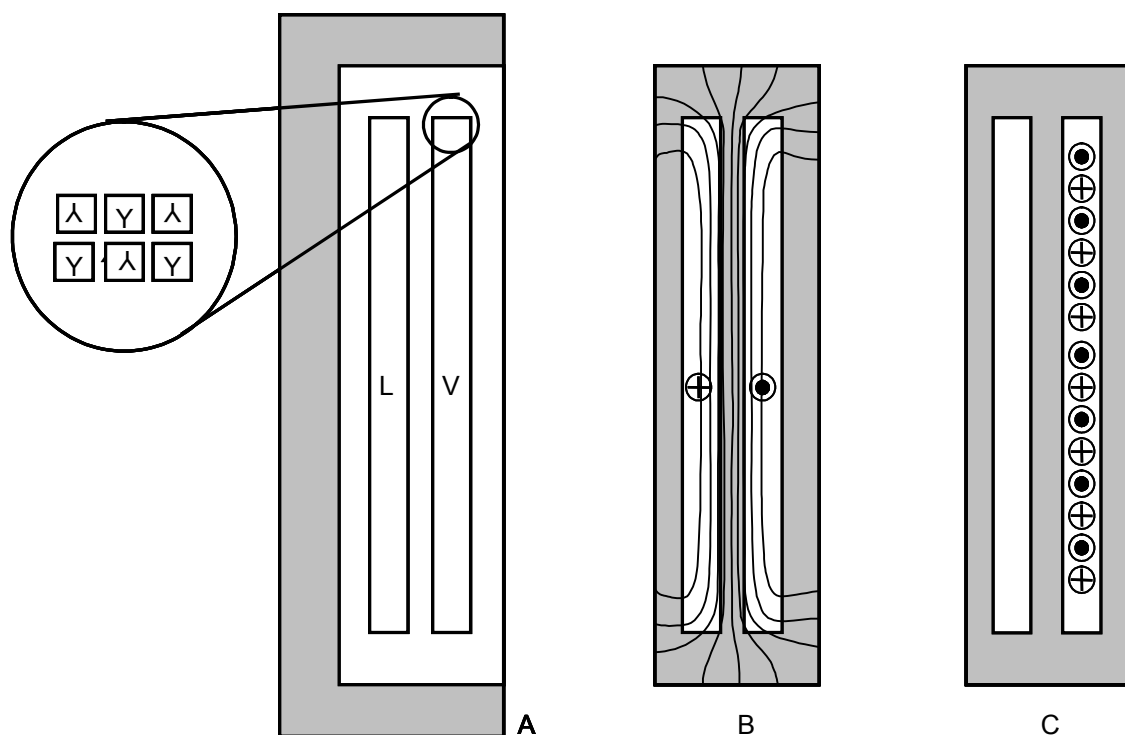
¹ As even harmonics in a double-star single-way diode rectifier or harmonics with $h = 6 \times K \pm 1$ (where K is an odd integer equal to 1, 3, ..., n) in a Y and Δ double way 12 pulse rectifier.

As for harmonic currents in phase opposition the following applies:

- 1) close coupling – harmonics in opposition are balanced between the interleaved valve windings; they produce a negligible leakage flux so that they only produce I^2R losses in the valve windings (see Figure 3);
- 2) no coupling – the intermediate yoke separates the magnetic circuits of the two pairs of valve-line windings; harmonics in opposition are balanced between each valve-line windings couple so that they produce both I^2R and eddy losses in both line and valve windings (see Figure 4) and stray losses in structural parts and line winding;
- 3) loose coupling obtained with double concentric valve windings – harmonics in opposition do not flow in the line winding as they are balanced between the valve windings where they produce both I^2R and eddy losses (see Figure 5) and stray losses in structural parts and in line winding;
- 4) loose coupling obtained with two line windings in parallel axially-displaced – harmonics in opposition are almost completely balanced between each valve-line windings couple so that the same considerations made for no coupling apply (see Figure 6) for the calculation of K_{we} . However, local loss distribution may differ significantly, see paragraph below and Annex C.

When rectifiers cause harmonic currents of opposite direction in loosely connected valve winding, the resulting magnetic leakage fields have significant radial components at the winding ends. These radial components generate local eddy losses in the uppermost and the lowest parts of each valve winding. The winding arrangement shown in Figure 6 requires special attention because of the high concentration of harmonic current of certain orders in the lowest part of the upper valve winding and in the highest part of the lower valve winding. Such service condition cannot be produced in a normal temperature rise test where the valves are not connected to the transformer. Therefore, if required by the purchaser, the effects of the harmonics in opposition shall be studied by means of the appropriate magnetic field simulation tools to validate the design solution.

Similar considerations, based on the mutual coupling of the windings, apply when more than three windings or shell type transformers are considered.



IEC 1722/11

Key

A winding arrangement in the core window

L line winding

B leakage flux produced by harmonics in phase

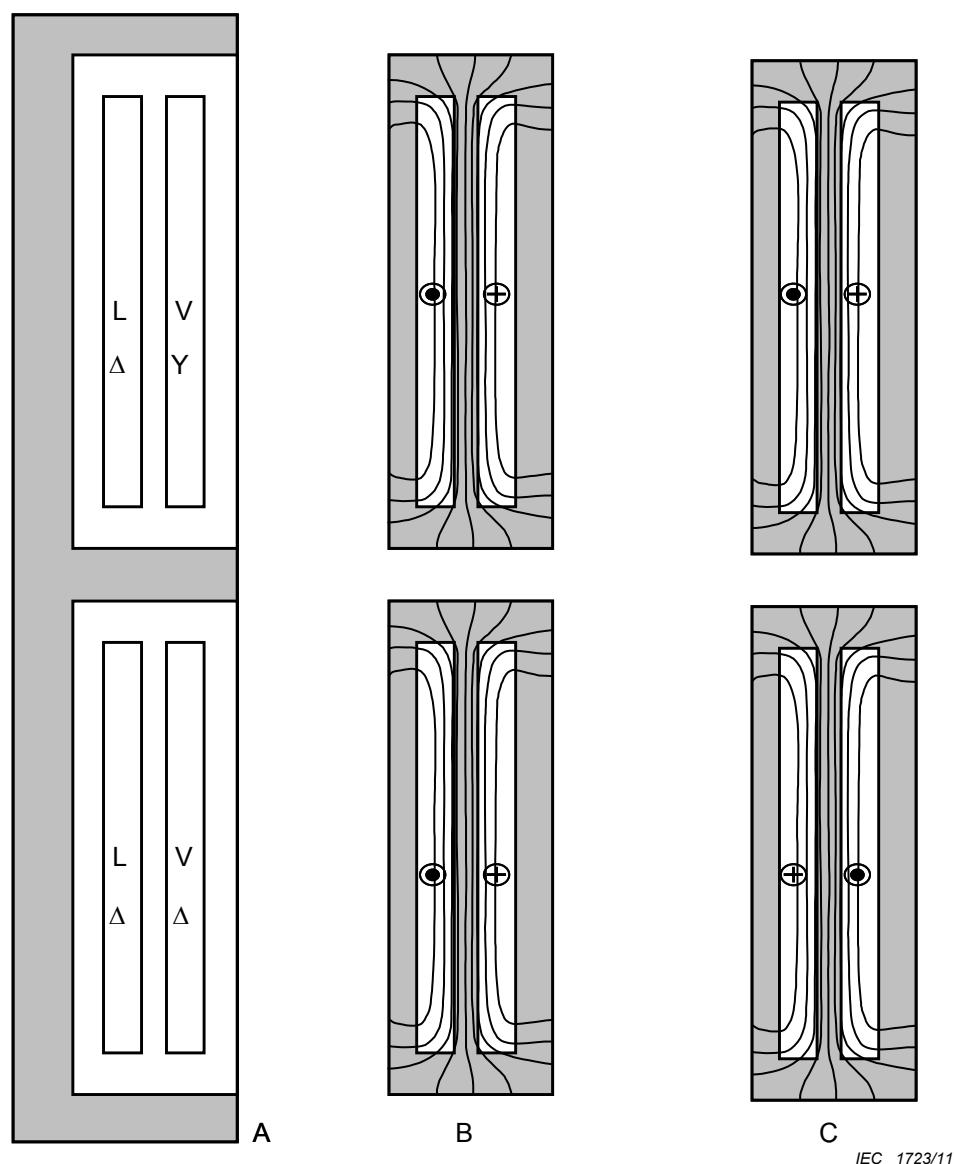
V interleaved valve windings

C leakage flux produced by harmonics with 180° phase displacement

Figure 3 – Leakage fields for a three-winding transformer with closely coupled valve windings

Coefficient $\left(\frac{P_{WE1h}}{P_{WE1}} \right)$ equals:

- Line winding: 1
- Valve windings:
 - 1 for harmonic current circulating in phase in both windings
 - 0 for harmonic current circulating in phase opposition in both windings.



IEC 1723/11

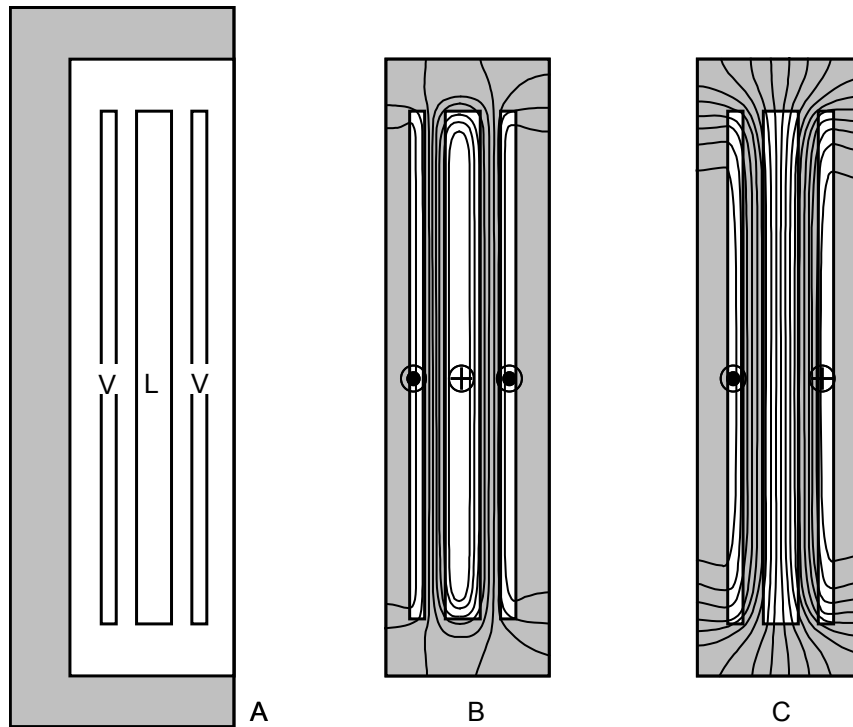
Key

- A winding arrangement in the core window
- B leakage flux produced by harmonics in phase
- C leakage flux produced by harmonics with 180° phase displacement
- L line windings
- V valve windings

Figure 4 – Leakage fields for a three-winding transformer with decoupled valve windings

Coefficient $\left(\frac{P_{WE1h}}{P_{WE1}} \right)$ equals:

- Line winding: 1 in both paralleled coils
- Valve windings: 1 in both windings



IEC 1724/11

Key

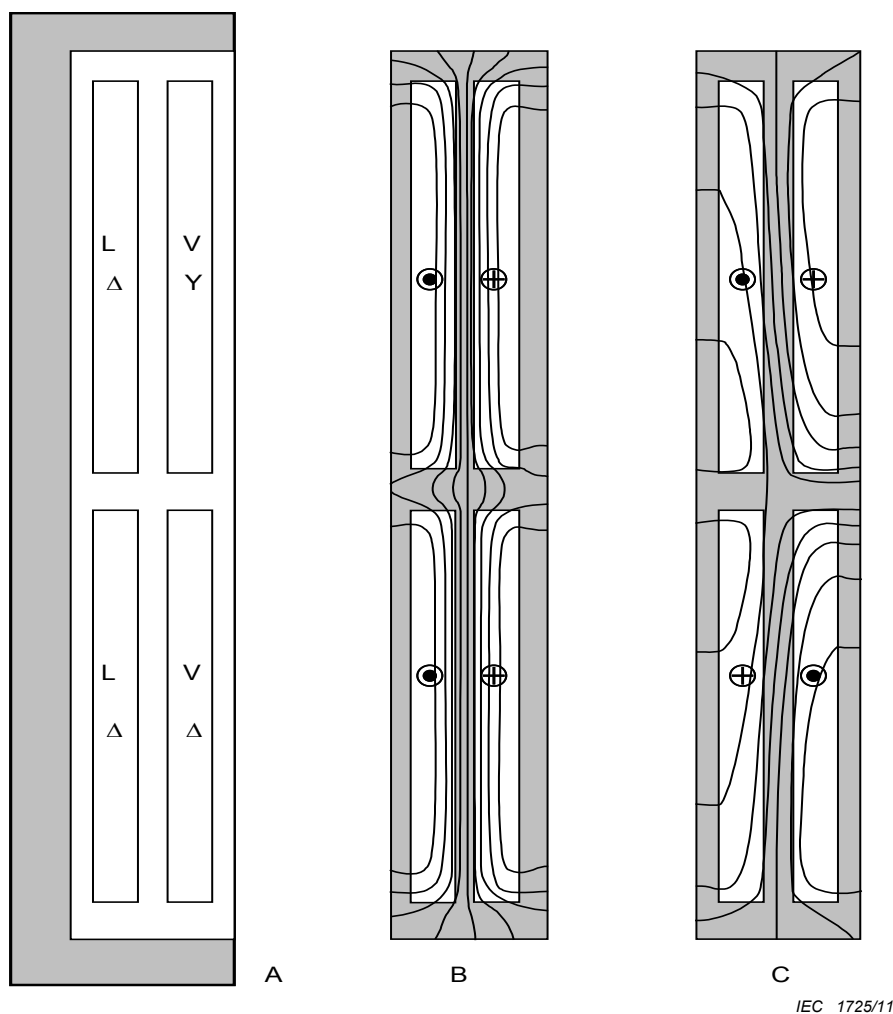
- A winding arrangement in the core window
- B leakage flux produced by harmonics in phase
- C leakage flux produced by harmonics with 180° phase displacement
- L line winding
- V valve windings

Figure 5 – Leakage fields for a three winding transformer with loosely coupled double concentric valve windings

Coefficient $\left(\frac{P_{WE1h}}{P_{WE1}} \right)$ equals:

- Line winding: 1
- Valve windings:
 - 1 for harmonic current circulating in phase in both windings
 - $x (>1)$ for harmonic current circulating in phase opposition in both windings.

x could be derived from either a computation or an implementation when possible, of a short-circuit test between valve windings.

**Key**

- A winding arrangement in the core window
- B leakage flux produced by harmonics in phase
- C leakage flux produced by harmonics with 180° phase displacement
- L line winding
- V valve windings

Figure 6 – Leakage fields for a three winding transformer with loosely coupled double-tier valve windings

Coefficient $\left(\frac{P_{WE1h}}{P_{WE1}} \right)$ equals:

- Line winding: 1
- Valve windings:
 - 1 for harmonic current circulating in phase in both windings
 - x for harmonic current circulating in phase opposition in both windings.

x could be derived from either a computation or an implementation when possible, of a short-circuit test between valve windings.

6.5 Losses in interphase transformers, current-balancing reactors, series-smoothing reactors and transductors

6.5.1 General

When interphase transformers, current-balancing reactors, series-smoothing reactors and transductors are integral parts of a transformer for connection to a static converter, the losses of these components shall be derived as stated below.

NOTE The rules laid down in this subclause do not imply specification of the individual pieces of equipment in the context of a standard.

6.5.2 Interphase transformers

The manufacturer shall supply the calculated iron losses at a frequency equal to the normal service frequency of the interphase transformer, and at a voltage calculated to provide the magnetic flux corresponding to operation of the converter at rated current, voltage and specified phase control. Data about current unbalance shall be discussed and agreed upon between the purchaser and the manufacturer. Capability to withstand the unbalance shall be demonstrated by calculation.

The losses in the winding shall be calculated as the product of the d.c. resistance and the square of the direct current in the winding.

6.5.3 Current-balancing reactors

The iron losses in current-balancing reactors are small and may be ignored.

NOTE The losses in the winding are either a part of the converter loss measurement, or are calculated as the product of the d.c. measured resistance and the square of the r.m.s. current in the winding.

6.5.4 Series-smoothing reactors

In general, reference shall be made to IEC 60076-6.

The iron losses caused by harmonic ripple current components are small and may be ignored.

NOTE The losses in the winding are either part of the converter loss measurement, or are calculated as the product of the d.c. resistance and the square of the direct current in the winding.

6.5.5 Transductors

Transductors are devices that allow a continuous and fine regulation of the d.c. voltage generated by the converter within a specified range. They are usually applied in conjunction with a.c. – d.c. diode based converters.

The degree of saturation in groups of magnetic cores determines the voltage drop in the transductors. A polarizing d.c. current imposed in auxiliary windings on the transductors governs the degree of saturation in the cores. A control circuit with or without an additional bias circuit governs the d.c. current. The voltage regulation is obtained by varying the d.c. current. The choice between control circuit with or without bias circuit depends on the converter control system design.

Transductors installed in converter transformers could be of two different types:

- Wound core: Transductors of this type are installed on the HV side of the converter transformer and they are series connected to the HV windings.
- Pass-through bar: Transductors of this type are installed on the LV connection bars system of the converter transformer and in such a way that each transductor is series connected directly to each converter valve arm. They are generally based on toroidal cores.

Wound core type transductors have the following losses:

- Core losses: The combined effect of the main a.c. current and the bias and control d.c. currents generates losses in the core lamination. For the time being, there is not any validated method to measure directly the core losses in transductor cores. How to estimate or calculate them has to be agreed between manufacturer and purchaser before the placement of the order.
- Load losses in the transductor a.c. windings: They shall be calculated at rated load based on the winding d.c. resistance at reference temperature and of the winding eddy losses at the fundamental frequency, enhanced by the corresponding factor F_{WE} for distorted current loading operation.
- Stray losses in transductor structural parts: They shall be calculated at rated load and fundamental frequency on the basis of proven empirical formulas and enhanced by the corresponding factor F_{SE} for distorted current loading operation.
- Losses in the bias windings: They shall be calculated at reference temperature based on the measured d.c. resistance and the d.c. bias currents.

Pass-through bar type transductors have the following losses:

- Core losses: The losses are generated in the wound cores by the combined effect of the main single way periodical current and the bias and control d.c. currents. For the time being, there is not any validated method to measure directly the core losses in transductor cores. How to estimate or calculate them has to be agreed between manufacturer and purchaser before the placement of the order.
- Load losses in the transductor bars: They shall be calculated at rated load on the basis of the bars d.c. resistance at reference temperature and of the bars calculated eddy losses at the fundamental frequency, enhanced by the corresponding factor F_{CE} for distorted current loading operation.

These losses are usually evaluated together with the transformer load losses.

NOTE 1 In DB converters, the LV side current harmonic spectrum is different from the transductor bars current spectrum. In fact, transductors, that are series connected to converter valves, are subject to a harmonics spectrum that includes both odd and even harmonics. For this reason, care should be taken in the evaluation of the busbar enhancement factor F_{CE} on the basis of the appropriate harmonics spectrum. (See A.5 for further explanations).

- Stray losses in transductor structural parts: In this type of transductor, due to the particular construction that minimizes the presence of structural metallic parts, they are generally negligible.
- Losses in the bias and control windings: They shall be calculated at reference temperature based on the measured d.c. resistance and the d.c. bias and control currents.

NOTE 2 In pass-through bar transductors, these losses are generally low compared to the other contributions, but the bias and control circuit resistance measurement is important as a reference value to be periodically checked during the transformer life.

6.6 Voltage drops in transformers and reactors

6.6.1 General

DC voltage drop introduced by converter transformers or reactors, depend on the respective reactive and the resistive component of the short circuit voltage:

- resistive direct voltage regulation: it shall be calculated from the loss measurements using the formulae given in 6.2.4 of IEC 60146-1-1:2009;
- inductive direct voltage regulation: it shall be calculated from the impedance measurements using the formulae given in 6.2.4 of IEC 60146-1-1:2009.

See also 7.2.2.

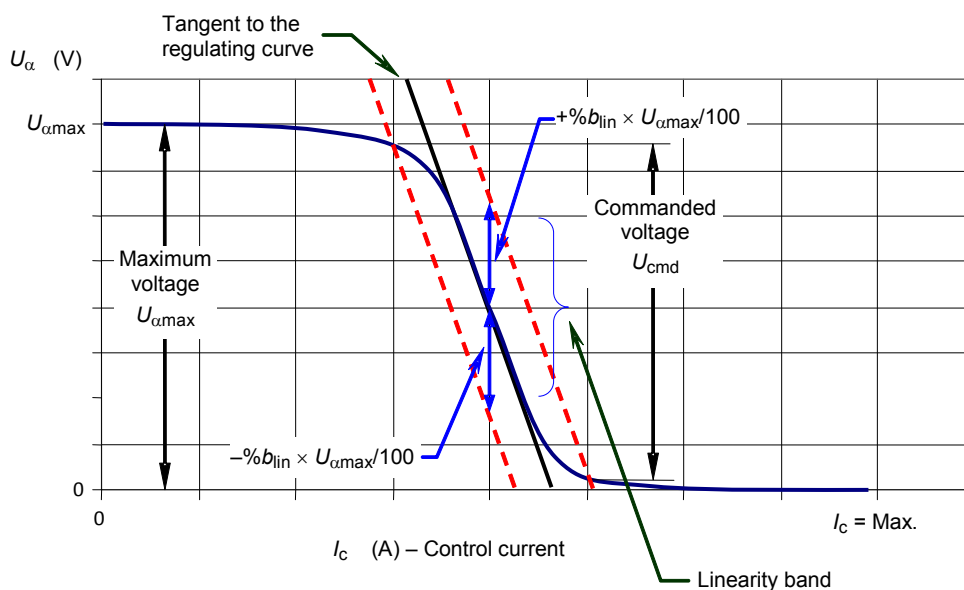
6.6.2 Transducers

The regulating capability of the transducers can be described by a curve traced at rated converter d.c. load and variable control current (see Figure 7). Transducers are identified by the following parameters:

- **Maximum voltage drop:** The maximum value of the d.c. voltage drop generated by the transducers at rated converter d.c. load and at the specified value of the control current. The value depends from transducer core physical and geometrical characteristics.
- **Commanded voltage regulation:** The linear part of the transducer regulating curve at rated converter d.c. load and variable control currents. This is defined as the portion of the regulating curve that is within the limits of a defined tolerance band.
- **Residual voltage regulation:** The non-linear part of the transducer regulating curve at rated converter d.c. load and variable control currents. It is the difference between the maximum voltage drop and the commanded voltage.

All the voltage drops described above are associated with a specific value of control current, which needs to be documented.

The purchaser shall prior of placing the order specify which of the above quantities are to be guaranteed (usually only the commanded voltage regulation is guaranteed). Corresponding tolerances on measured values of guaranteed quantities shall be agreed between purchaser and manufacturer.



IEC 1726/11

Figure 7 – Typical transducer regulating curve (with max voltage drop at zero control current) and tolerance band

The method of determination of the regulating curve (commonly named 'S curve') is subject to agreement between manufacturer and purchaser.

If the value U_{cmd} is guaranteed, then it shall be checked according to the following procedure and linearity band definition:

- from test data plot the regulating curve (commonly named 'S curve');
- trace the tangent to the curve in the inflection point of the 'S curve';
- trace the two lines parallel to the tangent shifted of the requested linearity band:

$$\text{band}_{\text{lin}} = \pm \% b_{\text{lin}} \times U_{\alpha} / 100 \quad (16)$$

- the two points of interception of the linearity band with the 'S curve' give the value of the commanded voltage U_{cmd} .

The value of the percent linearity band $\% b_{\text{lin}}$ has to be agreed between manufacturer and purchaser. A commonly accepted value for this parameter is:

$$\% b_{\text{lin}} = 15 \% \quad (17)$$

A commonly recognized method to calculate the transducer voltage drop is based on the following formulas:

$$U_{\alpha} = 6 \times f \times Sr \times B \quad \text{for double star converter.} \quad (18)$$

or

$$U_{\alpha} = 12 \times f \times Sr \times B \quad \text{for double bridge converter.} \quad (19)$$

where

B is the induction value (Tesla);

U_{α} is the voltage drop introduced on the d.c. side by the transducer (V);

f is the fundamental frequency (Hz);

Sr is the net transducer core section (m²);

$U_{\alpha\text{max}}$ is the voltage drop at the induction of saturation value B_s ;

U_{cmd} is the commanded voltage.

The S curve and corresponding value of U_{cmd} is obtained by referring to the B-H characteristic of the transducers cores material.

The U_{cmd} value, shall, if guaranteed, be assessed (either by calculations or special tests) at the factory acceptance test stage at the latest.

7 Tests for converter transformers

7.1 General

All tests shall be made in accordance with IEC 60076-1, IEC 60076-2 and IEC 60076-3 for oil-immersed transformers, and IEC 60076-11 for dry-type transformers, unless otherwise specified in this clause.

The transformer tests are divided into routine, type and special tests in accordance with 11.1.2, 11.1.3 and 11.1.4 of IEC 60076-1:2011 for oil-immersed transformers, and Clause 5 of IEC 60076-11:2004 for dry-type transformers.

In case of measurement of short circuit impedance between two valve windings is required, it may not be possible to reach 50 % of the rated current. This measurement will be carried out at the highest current allowable by the test equipment. The tolerance on this measurement has to be agreed with the purchaser. In case of interleaved valve windings, the short circuit impedance between them can be assumed as negligible.

7.2 Measurement of commutating reactance and determination of the inductive voltage drop

7.2.1 Commutating reactance

To measure the commutating reactance, the line-side terminals of the transformer shall be short-circuited. An alternating current of fundamental frequency as specified in item b) of 7.2.2 shall be passed through two consecutive phases of the same commutating group, and the voltage between these terminals shall be measured. The commutating reactance $2 \times X_t$ is equal to the inductive component of the impedance calculated from this measurement. At least two tests shall be carried out with different pairs of phases in each commutating group, and the arithmetic mean of these measurements shall be taken as the value of the commutating reactance.

When the same line winding feeds a commutating group connected in parallel or in series which commutates simultaneously, the windings corresponding to these groups shall be connected phase-by-phase in parallel for the above tests.

An alternative estimate of the commutating reactance can be deduced from the transformer impedance test results as follows:

The three phases of the valve winding are short-circuited. The short circuit impedance in p.u. is measured from the line side and referred to the rated power and the rated voltage of the valve winding. The commutating reactance X_t is equal to the inductive component of the short circuit impedance.

7.2.2 Inductive voltage regulation

The inductive voltage regulation shall be determined by either of the following two procedures.

- a) Calculation, using the formula

$$d_{xtN} = \frac{\delta \times q \times s}{2 \times \pi \times g} \times X_t \times \frac{I_{dN}}{U_{di0}} \quad (20)$$

- b) Measurement as described in 7.2.1, with an r.m.s. current equal to

$$\frac{\sqrt{2}}{4} \times \frac{\delta}{g} \times I_{dN} \quad (21)$$

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_{di0} is the ideal no-load direct voltage;

δ is the number of commutating groups commutating simultaneously per primary;

X_t is the inductive component of the short circuit impedance;

d_{xtN} is the inductive voltage regulation with current I_{dN} ;

d_{xt1} is the inductive voltage regulation with current I_1 .

In this case, the inductive component of the input voltage, expressed in p.u. of the rated voltage between terminals U_{v0} , represents the inductive voltage regulation d_{xt1} .

For the connections given in Table 1, the inductive voltage regulation can be calculated from the results of secondary short-circuit tests specified in last column, with the exception of connections 9 and 12. For these connections, the short-circuit test specified in 7.2.1 is recommended.

7.3 Measurement of voltage ratio and phase displacement

According to the IEC 60076-1, the voltage ratio shall be measured on each tap position. However, some converter transformers may have a very large number of taps. In this case, the manufacturer may agree with the purchaser to test just a subset of taps (as an example when coarse and fine regulations are present, it is sufficient to make measurements on each fine regulation step, having fixed a coarse step, and then one for each remaining coarse steps).

Tolerances of voltage ratio on taps other than the principal and of phase displacement angle on all taps have to be agreed between the purchaser and the manufacturer prior to the placing of the order. Without agreement between purchaser and manufacturer before the order, the tolerance of phase displacement should be $\pm 0,5^\circ$.

The measurement of voltage ratio and phase displacement can be obtained by one of the following methods (see Annex H):

- a) voltage ratio measurements;
- b) oscilloscope measurements.

The oscilloscope measurement checks the phase displacement with the sampling rate and the resolution of the measurement instruments while the voltage ratio measurement is independent from the device resolution needed to test the phase displacement: for this reason the measurement a) is recommended.

NOTE If transducers are present, purchaser and manufacturer should agree on how to check the polarity and ratio of the transducers bias and control circuits.

7.4 Dielectric tests

7.4.1 General

For single active part, dielectric tests shall be made in accordance with IEC 60076-3:2000.

For rectifier units including more than one active part in the same tank, the reference voltages for defining the dielectric tests are the line to line voltages of the primary and secondary terminals. It is often impracticable to test intermediate windings in formal compliance with IEC 60076-3:2000 and it should be agreed between the supplier and the purchaser as to which tests have to be omitted or modified before the time of placing the order. In case intermediate windings are tested, then their insulation level will be stated on the rating plate. If transducers are present, they shall be fully mounted at the time of dielectric tests.

7.4.2 Dielectric test between interleaved valve windings

The dielectric withstand capability of interleaved valve windings shall be tested as follows:

- a) Dielectric withstand capability between interleaved valve windings and ground. A single test is carried out with all interleaved valve windings terminals connected together. All the rest being in accordance with IEC 60076-3.
- b) Dielectric withstand capability between interleaved valve windings. The terminals of one of the two interleaved valve windings are connected together and grounded. The terminals of the other interleaved valve winding are connected together and an a.c. test voltage is applied for 1 min between these terminal and ground. The value of the test voltage is equal to double the rated a.c. voltage plus 500 V or 2 500 V, whichever is higher.

7.5 Load loss test

7.5.1 General

This test shall be performed to obtain the load loss in the transformer at rated current (I_1) and fundamental frequency.

The appropriate short-circuit connections for the tests are given in Table 1 for the commonly used connections.

The losses are measured for each short-circuit combination A, B and C. The measured loss values P_A , P_B and P_C are used to calculate the total guaranteed loss figure by the relevant equation in Table 1.

The test results shall be corrected to the following reference temperature:

- oil immersed transformers: 75 °C as defined in 11.1 of IEC 60076-1:2011;
- dry type transformers: according to the general requirements for tests in IEC 60076-11.

It is not required that the load loss shall be measured at two different frequencies as described in IEC 61378-2.

7.5.2 Load loss measurement in rectifier transformers with transducers in the same tank

During shortcircuit test for load loss and impedance measurements the presence of transducer cores add up both their losses and impedance to the main transformer. It also causes current and voltage wave shapes distortion. Measurements are then affected and if not properly compensated, may not comply with 11.4 of IEC 60076-1:2011 requirements (measurement of short circuit impedance and load loss). Special agreement needs to be reached between purchaser and manufacturer to perform these tests prior of placing the order. Several approaches are possible and some are illustrated in Annex G.

7.5.3 Test bus bars configuration for short circuit of high current valve windings

When selecting a configuration of external bus bars to short circuit high current valve windings, special care must be taken to estimate the increase of load loss, short circuit impedance and possibility of tank hotspots related to the presence of these test bus bars themselves.

7.6 Temperature rise tests

7.6.1 General

The temperature rise test procedure for oil-immersed transformers according to 7.3.2 of IEC 60076-2:2011 is modified as described in 7.6.2 and 7.6.3 below.

These subclauses also serve as guidance, as applicable, for the testing of dry-type transformers (see Clause 23 of IEC 60076-11:2004).

The purpose of the test is

- to establish the top oil temperature rise in steady-state condition, with dissipation of total loss equal to the loss at rated non-sinusoidal converter load current, and rated sinusoidal transformer voltage;
- to establish the winding temperature rise above oil under the same conditions;
- to establish the winding temperature rise above ambient for dry-type transformers.

The oil and winding temperature rise values are determined using the methods described in 7.6.2 and 7.6.3.

In some cases, it is possible that the test current needed to reach the specified test value of the total losses (see 7.6.1) to establish steady state oil temperature rise would overload some of the windings to unacceptable levels. Therefore it may be necessary to reduce the current/losses below the limits of applicability of correction formulas of 7.13 of IEC 60076-2:2011. In this case, purchaser and manufacturer shall agree on whether to extend the applicability of these correction formulas or to assess the temperature rises by means of calculations.

Whenever winding terminals are accessible, then winding temperature shall be measured at equivalent test current as per calculation in 7.6.3.

When winding terminals are not accessible (for example when multiple active parts are present in the same tank and/or in case of shifter windings), then these windings shall be considered as part of “internal design” and their temperature rise shall be assessed by means of calculations.

In case transducers are in the same tank of the active part(s), the temperature rise test can be carried out by one of the following modes to be agreed between purchaser and manufacturer at tender stage:

- a) the transducers remain fully assembled. In this case winding currents during tests do not present sinusoidal wave shapes. The additional loss due to these current harmonics shall be taken into account in the determination of the equivalent test current. Equivalent test current shall be measured in RMS;
- b) the transducers are either bypassed or their magnetic cores are removed in order to have sinusoidal wave shape of winding currents during the test.

7.6.2 Total loss injection

The total loss is the sum of the load loss plus the no-load loss and, if present, of IPT and transducers losses.

The load loss is the loss developed from the non-sinusoidal converter current (see 6.2). The no-load loss corresponds to rated transformer voltage.

The loss injected into the transformer shall be measured. The fundamental power-frequency current, I , shall be adjusted to give the specified test value of the total loss.

7.6.3 Rated load loss injection

7.6.3.1 Two-winding transformer

When the top oil temperature rise has been established, the test shall continue with a sinusoidal test current equivalent to the load loss at rated converter current. This condition shall be maintained for 1 h during which measurements of oil and cooling medium temperatures shall be made.

The equivalent test current is equal to

$$I_{eq} = I_1 \left(\frac{I_{LN}^2 \times (R_W + R_C) + (F_{WE} \times P_{WE1})}{I_1^2 \times (R_W + R_C) + P_{WE1}} \right)^{0,5} \quad (22)$$

At the end of the temperature rise test, the temperatures of the two windings shall be determined. This is done by a series of resistance measurements of the two windings that shall be made during the cooling period following the rapid disconnection of the supply and short circuits. For more details, see 7.3, 7.8, 7.9, 7.10 as well as C.1, C.2 and C.3 of IEC 60076-2:2011.

NOTE If the temperature rise test is carried out with the transducers mounted, then the current harmonics due to the presence of the transducers and their corresponding losses should be taken into account in the determination of I_{eq} .

7.6.3.2 Multi-winding transformer

The most common case is a three-winding converter transformer with two secondary windings having the same rated power. The secondary three-phase connection is either star-star with an interphase transformer, or star-star, delta-delta or one star- and one delta-connected winding.

The equivalent test current for each winding, in turn, shall be supplied and the winding temperature rise figures shall be obtained.

The general form for the equivalent current is

$$I_{eq} = I_1 \times \left(\frac{I_{WN}^2 \times (R_W + R_C) + (F_{WE} \times P_{WE1})}{I_1^2 \times (R_W + R_C) + P_{WE1}} \right)^{0,5} \quad (23)$$

NOTE 1 The two secondary valve windings per phase have close to 100 % magnetic coupling in the calculations developed in A.2 and A.3. Therefore, the eddy losses of all windings are based on six pulses in A.2 and twelve pulses in A.3 (see 5.2).

The equivalent test current value for each winding shall be obtained using specific values for resistance, eddy loss and enhancement factor for the winding.

NOTE 2 For transformers with heavy current busbar systems on the secondary side, it may be difficult or impossible to achieve a rapid disconnection of the short circuits. In that case, an agreement between the manufacturer and purchaser should be made concerning the temperature rise of the windings involved.

NOTE 3 Due to very low resistance values ($10^{-5} \Omega - 10^{-6} \Omega$) of high current valve windings, special care should be taken in the measurement of resistance of such windings to avoid significant errors.

NOTE 4 I_{WN} replaces I_L when the enhancement factor, F_{WE} , for the tested winding is calculated in accordance with Annex A.

The test shall be carried out in the following manner.

Both secondaries shall be short-circuited, and the equivalent primary current shall be supplied to obtain the temperature rise over the mean oil of the primary winding. Then each secondary winding shall in turn be short-circuited (leaving the other open) and primary current supplied to give the equivalent current in the tested secondary winding. These two tests give the winding temperature rises above mean oil for the secondary windings.

Alternatively, only the first test, with both secondary windings short-circuited, could be used. The measured winding temperature rise values of the secondary windings obtained from this test shall then be corrected in accordance with 7.13 of IEC 60076-2:2011.

7.6.3.3 Considerations about winding and tank hot spots

Equivalent test current is computed in order to produce the total losses equivalent to ones when windings are harmonically loaded. However eddy losses, with harmonics, increase in the winding end regions and a test with sinusoidal current is not able to reproduce the leakage field patterns that occur in service. In summary, therefore, it should be noted that this equivalent test current does not produce the local loss distribution within the winding that will occur when harmonic currents are present.

Particular attention is drawn to the fact that the hot spot temperature and its location, determined through a temperature rise test with sinusoidal current, is not necessarily the same that will be encountered during converter service. Therefore, because of the test procedure, care should be taken at the test stage to prevent thermal stresses beyond those occurring in service. The use of fiber optic sensors inside the windings are a useful tool for checking the

thermal behaviour of the unit either during the thermal test, or at on-load service. In case of non accessible intermediate circuit windings, fiber optics could be employed to assess thermal design.

To minimize undesired influence of external magnetic fields and to optimize the valve side design, the purchaser shall inform the transformer manufacturer about the mechanical layout of the bus bars.

7.6.4 Test of temperature rise on dry-type transformers

The test shall be made in accordance with any of the methods given in Clause 23 of IEC 60076-11:2004, with the following modification.

The load current shall be adjusted to correspond to load loss at rated converter current. The adjustment shall be carried out in accordance with Annex A and the equations in 7.6.3 for the equivalent current.

8 On load noise level with transducers and/or IPT

Whenever present, transducers and/or IPT are the main source of noise in converter transformers.

For both these devices, the noise generated is a function of the load currents and of system parameters outside the transformer itself.

On load noise measurements are either not possible or not representative of the operation conditions and there are no reliable methods to calculate the load noise level.

Table 1 – Connections and calculation factors

Connection number	Transformer connections		Valve connections	Pulse number	Commutation number	$\frac{U_{di}}{U_{v0}}$	Line side fundamental current factor ^a	Rated power ratio	Single way fundamental current factor ^b	Single way direct component factor ^b	Terminals to be short-circuited for short-circuit measurement			Guaranteed load losses	Guaranteed short-circuit impedance
	Line side	Valve side									A	B	C		
Single converter, single way connections															
5				6	3	$\frac{3}{\pi \times \sqrt{2}}$ (≈ 0,675)	$\frac{\sqrt{3}}{\pi \times \sqrt{2}}$ (≈ 0,390)	$2 \times \frac{\sqrt{2}}{2}$ (≈ 2 × 0,707)	$\frac{\sqrt{3}}{\pi \times 2\sqrt{2}}$ (≈ 0,195)	1/6 (≈ 0,167)	2U 2V 2W	3U 3V 3W		$\frac{(P_A + P_B)}{2}$	e_{XA} and e_{XB}
20				12	3	$\frac{3}{\pi \times \sqrt{2}}$ (≈ 0,675)	$2 \times \frac{\sqrt{3}}{\pi \times 2\sqrt{2}}$ (≈ 2 × 0,195)	$4 \times \frac{\sqrt{2}}{4}$ (≈ 4 × 0,353 6)	$\frac{\sqrt{3}}{\pi \times 4\sqrt{2}}$ (≈ 0,097 5)	1/12 (≈ 0,083)	A1	B1		$\frac{(P_{A1} + P_{B1})}{2}$ + $\frac{(P_{A2} + P_{B2})}{2}$	e_{XA1} and e_{XB1} e_{XA2} and e_{XB2}
											2U 2V 2W	3U 3V 3W			
											A2	B2			
											4U 4V 4W	5U 5V 5W			
Single converter, uniform double way connections															
8				6	3	$\frac{3 \times \sqrt{2}}{\pi}$ (≈ 1,350)	$\frac{\sqrt{6}}{\pi}$ (≈ 0,780)	1	$\frac{\sqrt{3}}{\pi \times \sqrt{2}}$ (≈ 0,390)	1/3 (≈ 0,333)	2U+ 2V+ 2W+ + 2U- 2V- 2W-			P_A	e_{XA}
9				12	3	$\frac{3 \times \sqrt{2}}{\pi}$ (≈ 1,350)	$\frac{\sqrt{6}}{\pi}$ (≈ 0,780)	2 × 1/2 (= 2 × 0,5)	-	-	2U 2V 2W	3U 3V 3W and 3U 3V 3W		P_C	e_{XA} and e_{XB}

Connection number	Transformer connections		Valve connections	Pulse number	Commutati on number	$\frac{U_{di}}{U_{v0}}$	Line side funda- mental current factor ^a	Rated power ratio	Single way funda- mental current factor ^b	Single way direct compo- nent factor ^b	Terminals to be short-circuited for short-circuit measurement			Guan- teed load losses	Guaranteed short- circuit impedance
	Line side	Valve side									A	B	C		
9	9.2			12	3	$\frac{3 \times \sqrt{2}}{\pi}$ (≈ 1,350)	$\frac{\sqrt{6}}{\pi}$	2 x 1/2 (=2x0.5)	$\frac{\sqrt{3}}{\pi \times 2\sqrt{2}}$ (≈ 0,195)	1/6 (≈ 0,167)	2U+ 2V+ 2W+ + 2U- 2V- 2W- + 3U+ 3V+ 3W+ + 3U- 3V- 3W-	3U+ 3V+ 3W+ + 3U- 3V- 3W-	2U+ 2V+ 2W+ + 2U- 2V- 2W- + 3U+ 3V+ 3W+ + 3U- 3V- 3W-	P_C	e_{XA} and e_{XB}
10	10.1			12	3	$\frac{3 \times \sqrt{2}}{\pi}$ (≈ 1,350)	$2 \times \frac{\sqrt{3}}{\pi \times \sqrt{2}}$ (≈ 2 x 0,390)	1	$\frac{\sqrt{3}}{\pi \times 2\sqrt{2}}$ (≈ 0,195)	1/6 (≈ 0,167)	2U 2V 2W	3U 3V 3W		$P_A + P_B$	e_{XA} and e_{XB}
12	10.2			12	3	$\frac{6 \times \sqrt{2}}{\pi}$ (≈ 2,701)	$\frac{2 \times \sqrt{6}}{\pi}$ (≈ 1,559)	2 x 1/2 (=2x0.5)	-	-	2U 2V 2W	3U 3V 3W	2U 2V 2W and 3U 3V 3W	P_C	e_{XA} and e_{XB}
13	13			12	3	$\frac{6 \times \sqrt{2}}{\pi}$ (≈ 2,701)	$\frac{2 \times \sqrt{6}}{\pi}$ (≈ 1,559)	1	-	-	2U 2V 2W	3U 3V 3W		$P_A + P_B$	e_{XA} and e_{XB}

	a	b
	refers to a transformer of voltage ratio 1	refers to valve current

NOTE The number of connections shown in the table compared with the first

Annex A (informative)

Determination of transformer service load loss at rated non-sinusoidal converter current from measurements with rated transformer current of fundamental frequency

A.1 General

Using the notations given in the list of symbols in 6.3, the following relations can be written for the winding loss.

$$\begin{aligned} P_{W1} &= R_W \times I_1^2 \times (1 + K_{WE} \times 1^x) \\ P_{W2} &= R_W \times I_2^2 \times (1 + K_{WE} \times 2^x) \\ &\vdots \\ P_{Wh} &= R_W \times I_h^2 \times (1 + K_{WE} \times h^x) \\ \hline P_W &= R_W \times I_L^2 + R_W \times K_{WE} \times \sum_1^n I_h^2 \times h^x \end{aligned} \quad (A.1)$$

Consequently

$$\frac{P_W - R_W \times I_L^2}{P_{W1} - R_W \times I_1^2} = \sum_1^n \left(\frac{I_h}{I_1} \right)^2 \times h^x \quad (A.2)$$

With $x = 2$ for windings, the enhancement factor is equal to

$$F_{WE} = \sum_1^n \left(\frac{I_h}{I_1} \right)^2 \times h^2 \quad (A.3)$$

In high-current busbar connection systems, the loss will follow the same basic rule as for windings, but the exponent, x , is lower. With $x = 0,8$, the enhancement factor for connections is equal to

$$\frac{P_C - R_C \times I_L^2}{P_{C1} - R_C \times I_1^2} = \sum_1^n \left(\frac{I_h}{I_1} \right)^2 \times h^{0,8} = F_{CE} \quad (A.4)$$

Based on other studies, the enhancement factor for the stray loss in structural parts is taken as equal to that of busbar systems.

$$F_{SE} = \frac{P_{SE}}{P_{SE1}} = F_{CE} \quad (A.5)$$

NOTE Subclause 9.1.2 (Losses and frequency) of IEC 61378-3: 2006, *Converter transformers – Part 3: Application guide* contains the explanation of the choice of $x = 2$ for windings and $x = 0,8$ for high current busbar and structural parts.

Further conventions of loss calculations:

- a) the winding loss P_{W1} is taken as the sum of the measured $I_1^2 \times R_W$ loss and the calculated eddy loss P_{WE1} .

$$P_{W1} = (I_1^2 \times R_W) + P_{WE1} \quad (\text{A.6})$$

- b) the sum of the eddy losses P_{CE1} from connections and the stray loss P_{SE1} in structural parts is equal to the measured total loss P_1 minus the winding loss P_{W1} according to a) and minus the measured $I_1^2 \times R_C$ loss of the connections.

$$P_{CE1} + P_{SE1} = P_1 - (P_{W1} + (I_1^2 \times R_C)) \quad (\text{A.7})$$

Total loss with distorted current:

$$P_N = I_{LN}^2 \times (R_W + R_C) + (F_{WE} \times P_{WE1}) + F_{CE} \times (P_{CE1} + P_{SE1}) \quad (\text{A.8})$$

All loss components in the above calculations are adjusted to the reference temperature (see 11.1.1 of IEC 60076-1:2011 and Clause 12 of IEC 60076-11:2004).

The respective components in the equations above shall be the sum of the values calculated for each winding separately.

The calculated eddy losses P_{WE1} in the windings together with the measured $I_1^2 \times R_W$ loss give an accurate value for the total winding loss P_{W1} .

The sum of stray loss from connections and structural parts $P_{CE1} + P_{SE1}$ can be derived with reasonable accuracy as the difference between the total measured loss P_1 minus the winding loss P_{W1} and minus the measured quantity $I_1^2 \times R_C$ of the d.c. loss of the connections.

A.2 Alternative method for calculation of the winding eddy loss enhancement factor

A more accurate estimate of the eddy loss enhancement factor for windings, F_{WE} described in A.1, can be made if the winding eddy loss components from axial and radial stray flux, P_{WEax1} and P_{WErad1} respectively, are known. These may be calculated at fundamental frequency using a finite element method of field analysis.

Since the distribution of the harmonic stray flux is the same as that of the flux at fundamental frequency in conventional windings consisting of individual strands, the following relationships may be derived.

Relation between strand dimensions and penetration depths:

$$X_{ah} = t \times \left(\frac{\mu_r \times \mu_0 \times \omega_1 \times h}{2 \times \rho} \right)^{0.5}$$

$$X_{rh} = s \times \left(\frac{\mu_r \times \mu_0 \times \omega_1 \times h}{2 \times \rho} \right)^{0.5}$$

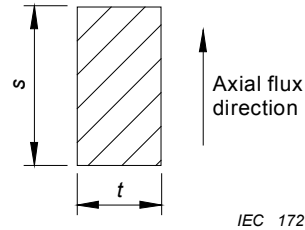


Figure A.1 – Cross-section of a winding strand

where

ω_1 is the pulse of fundamental frequency;

h is the harmonic order;

μ_0 is the permeability of vacuum;

μ_r is the relative permeability (for copper and aluminium $\mu_r = 1$).

The additional resistance, R_{ADh} , at frequency of order, $h \times \omega_1$, may be defined as

$$R_{ADh} = R_h - R_W \quad (\text{A.9})$$

where

R_h is the winding resistance at frequency, $h \times \omega_1$.

The increase of additional resistance R_{ADh} in relation to R_{AD1} fundamental frequency, is the same for all winding strands, regardless of the specific eddy loss of each strand and may be expressed as follows:

$$\frac{R_{ADh}}{R_{AD1}} = \frac{\Psi(X_h)}{\Psi(X_1)} \quad (\text{A.10})$$

where

$$\Psi(X_h) = 2X_h \times \frac{\sinh X_h - \sin X_h}{\cosh X_h + \cos X_h}.$$

Hence the expression for the winding enhancement factor F_{WE} may be expressed as:

$$F_{WE} = \frac{P_{WEax1}}{P_{WE1}} \times \sum_1^n \left(\frac{I_h}{I_1} \right)^2 \times \frac{\Psi(X_{ah})}{\Psi(X_1)} + \frac{P_{WErad1}}{P_{WE1}} \times \sum_1^n \left(\frac{I_h}{I_1} \right)^2 \times \frac{\Psi(X_{rh})}{\Psi(X_1)} \quad (\text{A.11})$$

For foil windings the winding enhancement factor may be taken as:

$$F_{WE} = \frac{P_{WEax1}}{P_{WE1}} \times \sum_1^n \left(\frac{I_h}{I_1} \right)^2 \times h^2 + \frac{P_{WErad1}}{P_{WE1}} \times \sum_1^n \left(\frac{I_h}{I_1} \right)^2 \times h^{0.5} \quad (\text{A.12})$$

Following examples A.3 to A.6 refer to oil filled transformers.

A.3 Example of the determination of transformer load loss under distorted current load

(Scheme as in Table 1, connection 5, magnetic coupling between valve windings practically 100 %, $p = 6$)

Converter rating

$$U_{di} = 354 \text{ V}$$

$$I_{dN} = 50\,000 \text{ A}$$

With interphase transformer in common tank

Transformer connection

Y y0y6

Transformer line winding voltage (kV)

30

Transformer valve winding voltage (kV)

$$0,354 \times \frac{\pi \times \sqrt{2}}{3} = 0,524$$

Rated transformer line current I_1 (A)

$$50\,000 \times \frac{\sqrt{3}}{\pi \times \sqrt{2}} \times \frac{0,524}{30} = 340,6$$

Rated transformer power S_R (kVA)

$$\sqrt{3} \times 30 \times 340,6 = 17\,700$$

Transformer valve winding power S_V (kVA)

$$2 \times \frac{\sqrt{2}}{2} \times 17\,700 = 2 \times 12\,516$$

Transformer valve winding rated current (A)

$$2 \times \frac{12\,516}{\sqrt{3} \times 0,524} = 2 \times 13\,783$$

Table A.1 – Specified harmonic currents and phase displacement in the valve windings

Harmonic order	Phase current in valve winding	Phase displacement between currents in valve windings	Calculated phase current in line winding
h	(A)	(°)	(A)
0	8 333,3	180	0,0
1	9 746,2	0	340,6
2	4 873,1	180	0,0
4	2 436,6	180	0,0
5	1 851,8	0	64,7
6	9,7	180	0,0
7	1 169,5	0	40,9
8	779,7	180	0,0
10	584,8	180	0,0
11	584,8	0	20,4
13	389,8	0	13,6
17	194,9	0	6,8
19	107,2	0	3,7
23	87,7	0	3,1
25	87,7	0	3,1

$$\sum_1^{25} \left(\frac{I_{hp}}{I_{1p}} \right)^2 = 1,056 = \left(\frac{I_{PN}}{I_{1P}} \right)^2 \frac{I_{PN}}{I_{1P}} = 1,028 \quad I_{PN} = 350 \text{ A}$$

$$\sum_0^{25} \left(\frac{I_{hv}}{I_{1v}} \right)^2 = 2,11 = \left(\frac{I_{SN}}{I_{1v}} \right)^2 \frac{I_{SN}}{I_{1v}} = 1,453 \quad I_{SN} = 14\,157 \text{ A}$$

Magnetic effect of even harmonics practically offset each other in valve windings and the eddy loss enhancement factors for valve and line windings are the same (refer to Figure 3 in 6.5).

$$F_{WE} = \sum_1^{25} \left(\frac{I_h}{I_1} \right)^2 \times h^2 = 3,57$$

In this example we assume busbars are fully compensated and magnetic effect of even harmonics practically offset each other in valve winding connections

$$F_{CE} = \sum_1^{25} \left(\frac{I_h}{I_1} \right)^2 \times h^{0,8} = 1,24 \text{ and } F_{SE} = F_{CE}$$

Valve current

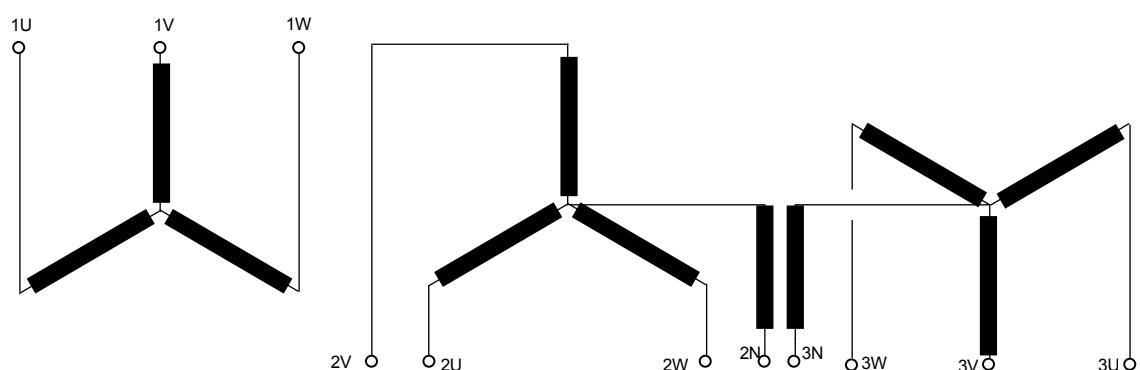
Direct component I_0 (A) $50\,000/6 = 8\,333,3$

Fundamental component I_{1v} (A) $50\,000 \times \frac{\sqrt{3}}{\pi \times 2\sqrt{2}} = 9\,746,2$

Measurements from test report in Table A.2.

Table A.2 – Resistance measurements at 20 °C winding temperature

Connected terminals (see Figure A.2)	Measured phase resistance	Corrected values at 75 °C Ω
1U – 1V – 1W	$\frac{1}{2} \times \frac{0,146\,8 + 0,146\,3 + 0,145\,7}{3} = 73,13 \times 10^{-3}$	$88,9 \times 10^{-3}$
2U – 2V – 2W	$\frac{1}{2} \times \frac{869 + 905 + 867}{3} \times 10^{-7} = 44,0 \times 10^{-6}$	$53,5 \times 10^{-6}$
3U – 3V – 3W	$\frac{1}{2} \times \frac{875 + 907 + 876}{3} \times 10^{-7} = 44,3 \times 10^{-6}$	$53,8 \times 10^{-6}$
n2 – 2N	$14,7 \times 10^{-6}$	$17,9 \times 10^{-6}$
n3 – 3N	$13,6 \times 10^{-6}$	$16,5 \times 10^{-6}$



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Figure A.2 – Terminal identification for winding connection Y y0y6

Measured load loss at 75 °C winding temperature, 50 Hz, and rated current $I_1 = 341$ A

$$P_1 = 124,3 \text{ kW}$$

I^2R loss at 75 °C and rated current for the transformer windings and connections

Primary 1U-1V-1W:	$I^2R = 3 \times 341^2 \times 88,9 \times 10^{-3} \times 10^{-3} =$	31,0 kW
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Secondary 2U-2V-2W:	$I^2R = 3 \times 13\,783^2 \times 53,5 \times 10^{-6} \times 10^{-3} =$	30,5 kW
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Secondary 3U-3V-3W:	$I^2R = 3 \times 13\,783^2 \times 53,8 \times 10^{-6} \times 10^{-3} =$	30,7 kW
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Winding and connections	Σ	92,2 kW
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Calculated eddy current loss at 75 °C		3,4 kW
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	Σ	95,6 kW
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Transformer eddy loss in the connections plus stray loss in structural parts

$$= P_{CE1} + P_{SE1} = P_1 - (\Sigma I^2R + P_{WE1}) = 124,3 - 95,6 = 28,7 \text{ kW}$$

Total load loss of the converter transformer at distorted current (I_{PN} and I_{SN})

$$P_N = (1,056 \times 31) + (14\,157/13\,783)^2 \times (30,5 + 30,7) + (3,57 \times 3,4) + (1,24 \times 28,7)$$

$$= 145 \text{ kW.}$$

Load loss of the interphase transformer

$$I^2R = 25\,000^2 \times (17,9 + 16,5) \times 10^{-6} = 21,5 \text{ kW}$$

The converter load current represents a transformer load of the fundamental current plus the content of harmonics under all load conditions.

NOTE The two secondary valve windings per phase have close to 100 % magnetic coupling. Therefore, the eddy losses of all windings are based on six pulses (see 6.5).

A different design of transformer may have close to zero magnetic coupling between the secondary valve windings. Such a design would require a calculation of F_{WE} and F_{CE} based on three pulses for the secondary valve winding.

A.4 Example of the determination of transformer load loss under distorted current load

(Scheme as in Table 1, connection number 12, magnetic coupling between electrical valve windings practically 100 %, $p = 12$)

Converter rating	$U_{di} = 1\,580\text{ V}$
	$I_{dN} = 5\,200\text{ A}$
Transformer connection	D d0y1
With two six-pulse bridges connected in series secondary	
Transformer line winding voltage (kV)	6,3
Transformer valve winding voltage (kV)	$1,580 \times \frac{\pi}{6 \times \sqrt{2}} = 0,585$
Rated transformer line current I_1 (A)	$5\,200 \times \frac{2 \times \sqrt{6}}{\pi} \times \frac{0,585}{6,3} = 753$
Rated transformer power S_R (kVA)	$\sqrt{3} \times 6,3 \times 753 = 8\,216$
Transformer valve winding power S_V (kVA)	$2 \times 0,5 \times 8\,216 = 2 \times 4\,108$
Transformer valve winding rated current (A)	$2 \times \frac{4\,108}{\sqrt{3} \times 0,585} = 2 \times 4\,054$

As the ratio between the LV windings turns numbers cannot equal exactly $\sqrt{3}$ then

Transformer rating	Primary	Secondary windings	
Rated power (kVA)	8 216	4 129	4 087
Rated system voltage (kV)	6,3	0,588	0,582
Rated transformer phase current (A)	$I_{1P} = 434,7$	$I_{1S} = 2\,341$	$I_{1S} = 4\,054$
Connection	D	d	y

Table A.3 – Specified harmonic currents and phase displacement in the line and valve windings

Harmonic order h	Phase current in delta valve winding (A)	Phase current in star valve winding (A)	Phase displacement between currents in valve windings (°)	Phase current in line winding (A)
1	2 340,8	4 054,4	0	434,7
5	444,8	770,3	180	13,8
7	280,9	486,5	180	8,7
11	140,4	243,3	0	26,1
13	93,6	162,2	0	17,4
17	46,8	81,1	180	0,9
19	25,7	44,6	180	0,5
23	21,1	36,5	0	3,9
25	21,1	36,5	0	3,9

$$\sum_1^{25} \left(\frac{I_{hp}}{I_{1p}} \right)^2 = 1,007 = \left(\frac{I_{PN}}{I_{1P}} \right)^2$$

$$\frac{I_{PN}}{I_{1P}} = 1,003 \quad I_{PN} = 755,5 \text{ A} = 436,2 \times \sqrt{3} \text{ A}$$

$$\sum_1^{25} \left(\frac{I_{hv}}{I_{1v}} \right)^2 = 1,056 = \left(\frac{I_{SN}}{I_{1v}} \right)^2$$

$$\frac{I_{SN}}{I_{1v}} = 1,028 \quad I_{SN} = 4 167,2 \text{ A} = 2 405,9 \times \sqrt{3} \text{ A}$$

Magnetic effect of harmonics 5, 7, 17 and 19 practically offset each other and the eddy loss enhancement factors for valve and line windings are the same (refer to Figure 3 in 6.5).

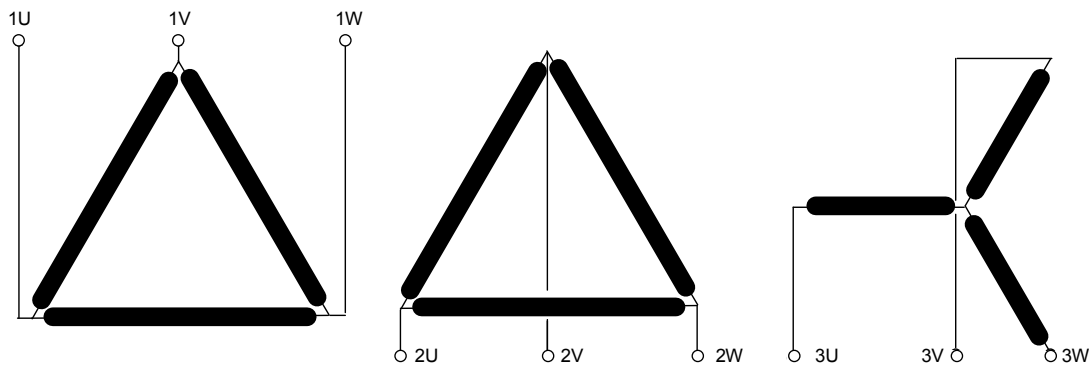
$$F_{WE} = \sum_1^{25} \left(\frac{I_h}{I_1} \right)^2 \times h^2 = 1,88$$

In this example we assume busbars are fully compensated and magnetic effect of harmonics 5, 7, 17 and 19 practically offset each other in valve winding connections

$$F_{CE} = \sum_1^{25} \left(\frac{I_h}{I_1} \right)^2 \times h^{0,8} = 1,045 \text{ and } F_{SE} = F_{CE}$$

Table A.4 – Measurements from test report

Connected terminals (see Figure A.3)	Measured phase resistance, corrected to value per phase at 21,5 °C	Corrected values at 75 °C Ω
1U – 1V – 1W	$1,5 \times 17,5 \times 10^{-3} = 26,3 \times 10^{-3}$	$31,7 \times 10^{-3}$
2U – 2V – 2W	$1,5 \times 0,374 \times 10^{-6} = 0,561 \times 10^{-6}$	$0,678 \times 10^{-6}$
3U – 3V – 3W	$0,5 \times 0,378 \times 10^{-6} = 0,189 \times 10^{-6}$	$0,228 \times 10^{-6}$



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Figure A.3 – Terminal identification for winding connection D d0y1

Measured load loss at 75 °C, 50 Hz, and rated current $I_{1P} = 434,7$ A and $I_{1S} = 2\,341$ A or 4 054 A

$$P_1 = 49,77 \text{ kW}$$

$$\text{Primary } 1U-1V-1W: \quad I^2R = 3 \times 434,7^2 \times 31,7 \times 10^{-3} \times 10^{-3} = 17,97 \text{ kW}$$

$$\text{Secondary } 2U-2V-2W: \quad I^2R = 3 \times 2\,341^2 \times 0,678 \times 10^{-6} \times 10^{-3} = 11,15 \text{ kW}$$

$$\text{Secondary } 3U-3V-3W: \quad I^2R = 3 \times 4\,054^2 \times 0,228 \times 10^{-6} \times 10^{-3} = 11,24 \text{ kW}$$

$$\text{Winding and connections} \quad \Sigma \quad 40,36 \text{ kW}$$

$$\text{Calculated eddy current loss at 75 °C} \quad 1,39 \text{ kW}$$

$$\Sigma \quad 41,75 \text{ kW}$$

Transformer eddy loss in the connections plus stray loss in structural parts

$$P_{CE1} + P_{SE1} = P_1 - (\Sigma I^2R + P_{WE1}) = 49,77 - 41,75 = 8,02 \text{ kW}$$

Total loss of the converter transformer at distorted current (I_{PN} and I_{SN})

$$P_N = (1,007 \times 17,97) + (1,056 \times (11,15 + 11,24)) + (1,88 \times 1,39) + (1,045 \times 8,02)$$

= 52,7 kW.

NOTE The two secondary valve windings per phase have close to 100 % magnetic coupling. Therefore, the eddy losses of all windings are based on twelve pulses (see 6.5).

A different design of transformer may have close to zero magnetic coupling between the secondary valve windings. Such a design would require a calculation of F_{WE} and F_{CE} based on six pulses for the secondary valve winding.

A.5 Example of the determination of transformer load loss under distorted current load. Multi-active parts in a same tank: bridge case

(Scheme as in Table 1, connection number 10.2, magnetic coupling between electrical valve windings practically 0 %, $p = 12$)

Rectifier transformer combination with in the same tank:

- 1 regulating autotransformer;
- 2 rectifier transformers, 2 primary windings star and delta connected, 2 secondary windings delta connected;
- 12 transducers.

for contribution of $U_{di} = 1\,792$ V d.c. no load (1 600 V d.c. on load), $I_{dN} = 55$ kA d.c. in supplying an aluminium potline. Supply voltage 132 kV.

Transducer rating:

Number:	12
Commanded voltage regulation:	50 V d.c.
Current:	valve current

Valve current: Ideal wave form $c = T/3$

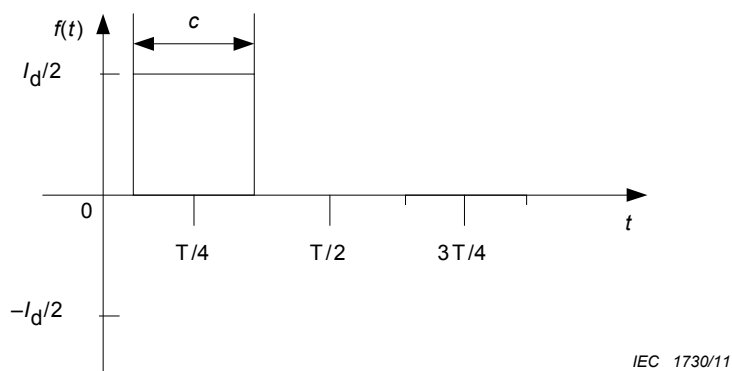


Figure A.4 – Valve current DB connection rectangular shape positive shape

Table A.5 – Resulting current harmonics

Harmonic order h	Current in valve line (A)	Harmonic order h	Current in valve line (A)
0	9 166,7	8	857,7
1	10 720,8	10	643,2
2	5 360,4	11	643,2
3	53,6	13	428,8
4	2 680,2	17	214,4
5	2 037,0	19	117,9
6	10,7	23	96,5
7	1 286,5	25	96,5

- continuous componen = $55\,000 / 6 = 9\,166,7\text{ A}$
- rms fundamental component = $55\,000 \times \frac{\sqrt{3}}{\pi \times 2\sqrt{2}} = 10\,720,8\text{ A}$
- $\sum_0^{25} \left(\frac{I_{hv}}{I_{1v}} \right)^2 = 2,110\,0$
- $I_{VN} = \left(\sum_0^{25} I_h^2 \right)^{0,5}$ total rms = 15 573 A
- total rms (rectangular wave) = 15 877 A
- $F_{CE} = F_{SE} = \sum_1^{25} \left(\frac{I_h}{I_1} \right)^2 \times h^{0,8} = 1,924\,6$

Rectifier transformers rating:

Number	2
Primary voltage:	50 kV
Secondary voltage ($U_{v0} = 1\,792/1,35\text{ V}$):	1 327 V
Rated line side current	
($I_1 = 55\,000 \times 0,390 \times 1\,327/50\,000$):	569 A
Rated primary power:	49,3 MVA
Rated secondary power: ($\frac{S_{1S}}{S_R} : 1$)	49,3 MVA
Rated valve side current:	21 442 A

Valve side current: Ideal wave form $c = T/3$

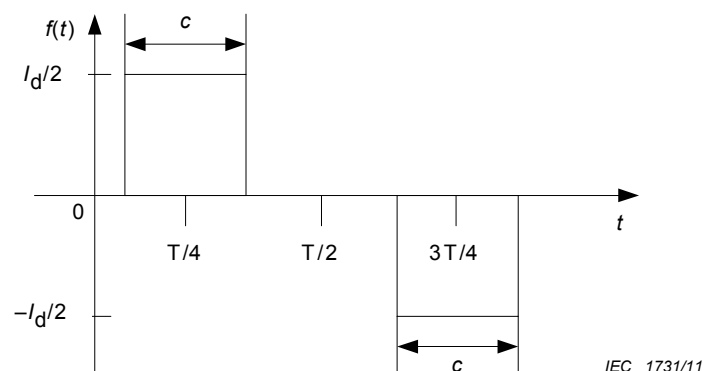


Figure A.5 – Valve current DB connection rectangular shape positive and negative shape