

BS IEC 61378-3:2015



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Converter transformers

Part 3: Application guide

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The UK participation in its preparation was entrusted to Technical Committee PEL/14, Power transformers.

A list of organizations represented on this committee can be obtained on request to its secretary.

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

CONVERTER TRANSFORMERS –**Part 3: Application guide****FOREWORD**

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International Standard IEC 61378-3 has been prepared by IEC technical committee 14: Power transformers.

This second edition cancels and replaces the first edition published in 2006 and constitutes a technical revision.

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

- a) revision of clause on losses to reflect the changes introduced by the second edition of IEC 61378-1;
- b) addition of a new clause about design review of converter transformer for both industrial and HVDC applications;
- c) addition of content for transformer connected to voltage source converters;
- d) reference to the work of CIGRE JWG A2/B4.28 on HVDC transformers.

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

FDIS	Report on voting
14/803/FDIS	14/808/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.

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

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

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

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- withdrawn,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

INTRODUCTION

0.1 General

IEC 61378 series is written in three parts:

- Part 1 applies to transformers associated with general "Industrial" converter uses. (Copper making, aluminium smelting and the electrolysis of certain gases).
- Part 2 applies to transformers required for HVDC applications.
- Part 3 is this application guide which contains the topic headings described in 0.2 to 0.13.

The scope of IEC 61378-1 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.

IEC 61378-2 covers converter transformers used in "HVDC Applications". There are two types of HVDC power transmission systems known generically as "back to back" and "transmission" schemes. The operation and evaluation of transformers operating within these two systems are covered by Part 2 and the present part of IEC 61378.

Neither IEC 61378-1:2011 nor IEC 61378-2:2001, explicitly include in their scope transformers connected to voltage source converters (VSC). Because VSC applications are becoming more and more common, some guidance is provided in this standard.

0.2 Rating data (Clause 5)

In both IEC 61378-1 and IEC 61378-2, the method of rating converter transformers is different to that used historically. In the traditional method, the r.m.s. value of current was used in defining the nameplate rating of the transformer. IEC 61378 has introduced a fundamental change in the method of defining the rating of transformers. The concept of using the fundamental components of voltage and current as the basis for the transformer nameplate rating is explained. The nameplate rating derived from these fundamental components becomes the basis for the guaranteed impedances and losses.

0.3 Winding configurations (Clause 6)

There are a large number of winding connections and configurations that are specific to converter transformers for both industrial and HVDC applications. They have been developed over many years. The operating characteristics of the various rectifier connections are mostly covered in IEC 60146 series. In the present part of IEC 61378, the connections are discussed in so far as they affect the construction and some operational aspects of the transformer.

The use of regulating schemes is common in industrial applications. The present part of IEC 61378 covers the principles for a number of these schemes.

0.4 Tappings and impedances (Clause 7)

The impedance of transformers for HVDC applications requires special attention and design solutions. The requirements primarily concern the limitation of the impedance variability over the whole tapping range, the limitation of the impedance difference between transformers and in some applications, the impedance difference between star and delta windings. This standard discusses these requirements and their practical aspects.

In general, the tapping range in converter transformers is wider than in conventional transformers. The impact of the wider tapping range on the transformer and the tap-changer is discussed in this standard.

0.5 Insulation aspects and dielectric tests (Clause 8)

Two aspects are covered in Clause 8. First, the increasing use of “hybrid” insulation systems in transformers for industrial applications. Secondly, the ability of transformer insulation structures of HVDC transformers when tested with d.c. voltage and in service.

The basic principles, the methods of testing and the test voltage levels used for both a.c. and d.c. testing are discussed. The safety margins associated with the proposed testing regime are also reviewed.

0.6 Losses (Clause 9)

The present part of IEC 61378 details the derivation of the principles, testing and calculation methods used that take into account the effects of non-sinusoidal load currents on converter transformers of all types.

The principles of testing at two frequencies for HVDC applications are detailed along with a worked example of the calculation. The losses derived from these tests and calculations are used as the base for specifying the test losses and currents to be used in establishing the oil and winding gradients during the thermal testing.

0.7 Core and sound aspects (Clause 10)

The effects of voltage harmonics and a d.c.-bias circulating-current on the performance and construction of the core are discussed and summarized.

The causes of sound and the differences that may be expected between conventional factory sound measurements and those to be expected and experienced at site are reviewed.

The latest methods of assessment of sound associated with converter transformers are discussed.

0.8 Transformer specification (Clause 11)

Transformers for converters differ significantly from power transformers with respect to the transformer specification. An outline of the details required in any specification is included as part of the guide for both technical and functional types of specification.

Some guidance as to what should be specified by the purchaser and what should be expected from the manufacturer during the tender and order process is given.

0.9 Short circuit considerations (Clause 12)

In conventional power transformers, the calculation of the short circuit currents within the windings are dependent solely on the impedance and resistance components of the transformer and supply to which it is connected.

In the case of transformers used to supply converter applications, there are fault conditions within the converter that need to be considered where the peak value of the fault currents may be higher than those derived for conventional power transformers. These conditions are detailed in the present part of IEC 61378.

0.10 Components (Clause 13)

In the design of transformers for both industrial and HVDC converter applications, the choice and operation of the on-load tap-changer is crucial. The present part of IEC 61378 outlines some of the principles governing the use of tap-changers in these applications.

In the HVDC application, the choice and integration of the valve-side bushings into the overall design is of vital importance.

The general requirements and recommendations for the construction, integration of the bushings with the transformer and testing are detailed. An IEC standard specifically for HVDC bushing is in preparation and the recommendations in the present part of IEC 61378 draws upon the requirements of the new standard.

0.11 Maintenance (Clause 14)

Statistics suggest that the HVDC transformers require maintenance to a high standard. Those items that require particular attention are on-load tap-changers and valve-side bushings. Attention is drawn in this standard to maintenance requirements.

0.12 Monitoring and on-site investigations (Clause 15)

Transformer monitoring is recommended if on-site problems are to be minimized and in this respect, condition monitoring is discussed. The present part of IEC 61378 also presents recommendations for the procedure and practices to be followed in the event of a failure at site. These recommendations are made so that vital evidence and data are not destroyed or contaminated at the initial stages of the investigation.

The use of condition monitoring for this application is also discussed in Clause 15.

0.13 Additional sources of information

The preparation of the present part of IEC 61378, specifically for IEC 61378-2 HVDC converter applications, was significantly influenced by the working papers on various topics of CIGRE Joint Working Group 12/14.10.

CONVERTER TRANSFORMERS –

Part 3: Application guide

1 Scope

This part of IEC 61378 provides information to users about specific topics related to industrial and HVDC converter transformers with design, construction, testing and operating conditions differing from conventional transformers used in power systems. In addition, it is the aim of the present part of IEC 61378 to provide manufacturers with the technical background that forms the basis for the principles used within IEC 61378-1 and IEC 61378-2.

It is intended that this part of IEC 61378 is used to supplement and not replace or supersede the application guide for power transformers, IEC 60076-8, since many of the general principles contained within it are equally applicable to converter transformers.

2 Normative references

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

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

IEC 60076-5:2006, *Power transformers – Part 5: Ability to withstand short circuit*

IEC 60076-14:2013 *Power transformers – Part 14: Liquid-immersed power transformers using high-temperature insulation materials*

IEC 60296, *Fluids for electrotechnical applications – Unused mineral insulating oils for transformers and switchgear*

IEC 60422, *Mineral insulating oils in electrical equipment – Supervision and maintenance guidance*

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

IEC 61378-2:2001, *Converter transformers – Part 2: Transformers for HVDC applications*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 61378-1 and IEC 61378-2 apply.

4 Symbols and abbreviations

Symbol	Meaning	Units
I_1	r.m.s. value of the fundamental component of the rated line side current	A
I_x	r.m.s. value of the load loss test current at frequency f_x	A

Symbol	Meaning	Units
I_{LN}	r.m.s. value of the non-sinusoidal in-service load current in the winding under consideration at rated converter load	A
I_h	r.m.s. value of harmonic current having order number h	A
I_{eq}	r.m.s. value of the equivalent sinusoidal test current giving the winding in-service load loss	A
h	harmonic order number	
U_1	r.m.s. value of the fundamental component of the line-to-line rated voltage	V
S_r	Rated power of the transformer	VA
P_1	Transformer load losses measured at current I_1	W
P_x	Transformer load loss measured at current I_x	W
$I_1^2 R$	Ohmic losses at rated current I_1	W
R	d.c. resistance of windings including internal leads	Ω
P_{WE1}	Eddy losses in windings with current I_1	W
P_{SE1}	Stray losses in structural parts (excluding windings) with current I_1	W
P_N	Transformer load loss in service with current I_N	W
f_1	Rated frequency and also the fundamental frequency (50 Hz or 60 Hz)	Hz
f_x	Frequency ≥ 150 Hz used to determine the distribution of eddy losses (HVDC transformer applications only, not applicable for industrial transformer applications)	Hz
f_h	Frequency at harmonic order number h	Hz
F_{WE}	Enhancement factor for winding eddy losses	
F_{SE}	Enhancement factor for stray losses in structural parts	
K_h	Ratio of the current I_h to the rated current I_1	
U_{ac}	a.c. separate source test voltage for the valve windings (r.m.s. value.)	V
U_m	Highest system voltage of the line winding	V
U_{dm}	Highest d.c. voltage per valve bridge	V
U_{dc}	d.c. separate source test voltage for the valve windings	V
U_{pr}	Polarity reversal test voltage for the valve windings (d.c. voltage)	V
U_{vm}	Maximum phase to phase a.c. operating voltage of the valve windings of the converter transformer	V
N	Number of six-pulse bridges in series from the neutral of the d.c. line to the rectifier bridge connected to the transformer	

NOTE "Valve side" and "line side" define the external connections of the transformer windings. Line side refers to the winding connected to the a.c. network and valve side to the winding connected to the converter.

5 Rating data

IEC 61378-1 and IEC 61378-2 state that the rating characteristics of the transformer are expressed in steady state sinusoidal quantities of current and voltage at the rated fundamental frequency. The guaranteed losses, impedances and sound level shall correspond to these values. The rated voltage and current refer to the fundamental quantities, line-to-line voltage and line current.

Fundamental components are selected to establish a common platform for guaranteed quantities such as losses and impedances independent of the operating conditions and thus the spectrum of harmonic content. It should be noted that the tests in establishing the operating characteristics can only be carried out with sinusoidal quantities.

When industrial transformer units are provided with transducers (saturable reactors) in their tank, transductor cores make the test challenging because of the distortion of current and voltage wave shapes they cause. An agreement on the test modalities needs to be reached between the supplier and the purchaser before signing of the contract. No method has been commonly accepted. Some are presented in Annex G of IEC 61378-1:2011.

Guaranteed temperature rise values are relevant for a specific loading condition as defined by agreement between purchaser and manufacturer. As a converter transformer is exposed to a current with a certain harmonic content, the actual losses will deviate from the losses developed with a true sinusoidal current. In general, harmonics in the current will give rise to an enhancement in load losses as compared to operation with true sinusoidal current.

From the aspect of transformer design, it is important to distinguish between

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

Information about the converter application should be supplied in the transformer specification.

The no-load loss guaranteed value is defined by the rated sinusoidal voltage.

The actual load loss in converter operation is estimated with sufficient accuracy by the calculation procedure presented in IEC 61378-1:2011, 6.2 and in IEC 61378-2. From this set of formulae the corresponding test current for establishing the corresponding temperature rise can be deduced (see IEC 61378-1:2011, 7.6 or IEC 61378-2:2001, 10.5).

It should also be noted that the actual load current in operation may be higher than the rated current, when measured by an instrument reading r.m.s. values of current, since the rated current on the nameplate refers to the fundamental component of the load current.

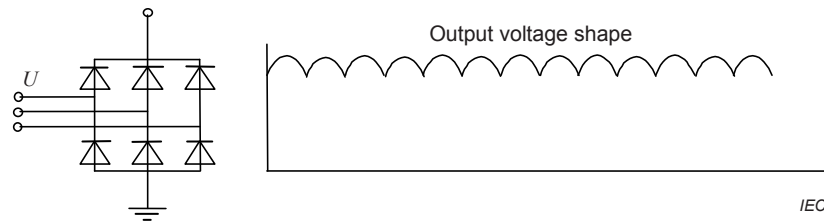
6 Winding configurations

6.1 General

This clause describes the different versions of arrangement of windings that can exist in both industrial and HVDC applications.

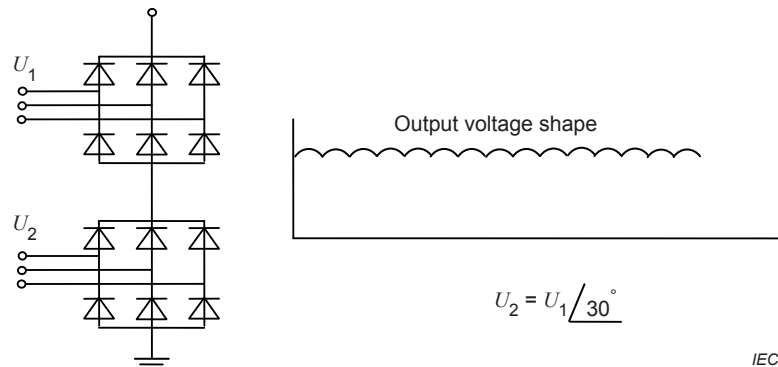
In general, the windings will be arranged to provide a six-pulse converter bridge from a balanced three-phase system. The converter will carry current twice from each phase for a maximum duration of 120 electrical degrees or one third of a cycle, once in positive and once in negative direction. See Figure 1.

Two or more six-pulse bridges may be connected in series or parallel. When supplying the individual bridges with line-side, three-phase voltages displaced in time, the harmonic content in line-side currents and valve-side voltages and currents will be reduced. With two six-pulse bridges connected in a so-called twelve-pulse arrangement, the two three-phase supplies shall be separated by 30 electrical degrees. Still higher pulse numbers on the converters require less separation between the systems. See Figures 2 and 3.



NOTE The symbol of rectifier means either diode or thyristor.

Figure 1 – Bridge connection for six-pulse arrangement



NOTE The symbol of rectifier means either diode or thyristor.

Figure 2 – Bridge connection for twelve-pulse arrangement

NOTE 1 Increased pulse number reduces the harmonic content in voltage and currents.

A common arrangement to reach two three-phase systems with a 30-electrical-degree separation is two transformers connected to a common bus on the line side. One transformer has the same winding connection on the line and valve sides, star-star or delta-delta. The other transformer has the connection star-delta or delta-star.

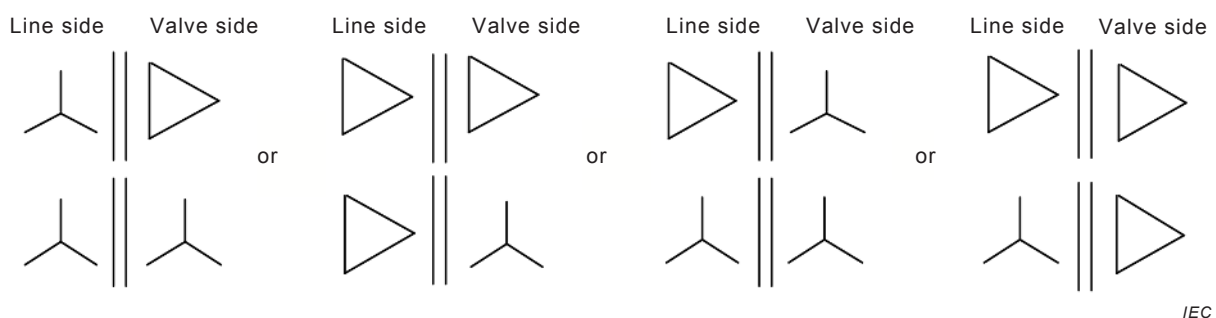


Figure 3 – Transformer connections star-delta and star-star or alternatively, delta-delta and delta-star to give a 30 electrical degree separation between the valve-side voltages

Two identical transformers with a winding connection making a 15 electrical degrees shift between line-side and valve-side voltages can be used to provide a 30 degree shift between the two valve-side voltages. One transformer is connected for positive rotation (1U-2U, 1V-2V and 1W-2W) and the other with negative rotation (1U-2V, 1V-2U and 1W-2W). This arrangement will give +15 electrical degrees and -15 electrical degrees on the valve side as compared to the line side.

A 15 electrical degree shift can preferably be reached by one of the two windings connected in zigzag or as an extended delta. See Figure 4.

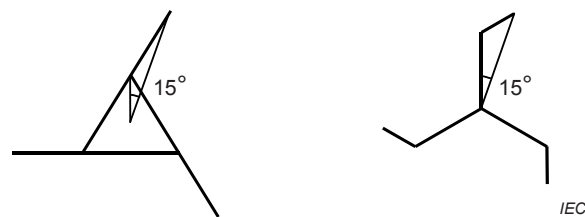


Figure 4 – 15° phase shifting is preferably realized by extended delta or zigzag connection

NOTE 2 The two connections can also be used for other shifting angles such as 7,5 electrical degrees for twenty-four-pulse bridges.

Industrial units with tertiary windings loaded with filter and compensation are covered in IEC 61378-1:2011, 5.7. It should be noted that the connection of the filter to the tertiary winding will lead to a higher than rated voltage. Therefore the fundamental current flowing through the filter impedance will be higher than the rated current as defined in the clause just mentioned. So it is important that the system engineer takes into account this phenomenon when specifying maximum tertiary winding fundamental current.

6.2 Industrial applications

6.2.1 Rectifier

In general, converter transformers for industrial application will be designed for a fairly high current on the valve side. The valve windings shall therefore have simple connections such as star or delta.

For some industrial applications with high DC currents and low DC voltage, it is often of advantage to use a double-star arrangement instead of bridge configuration.

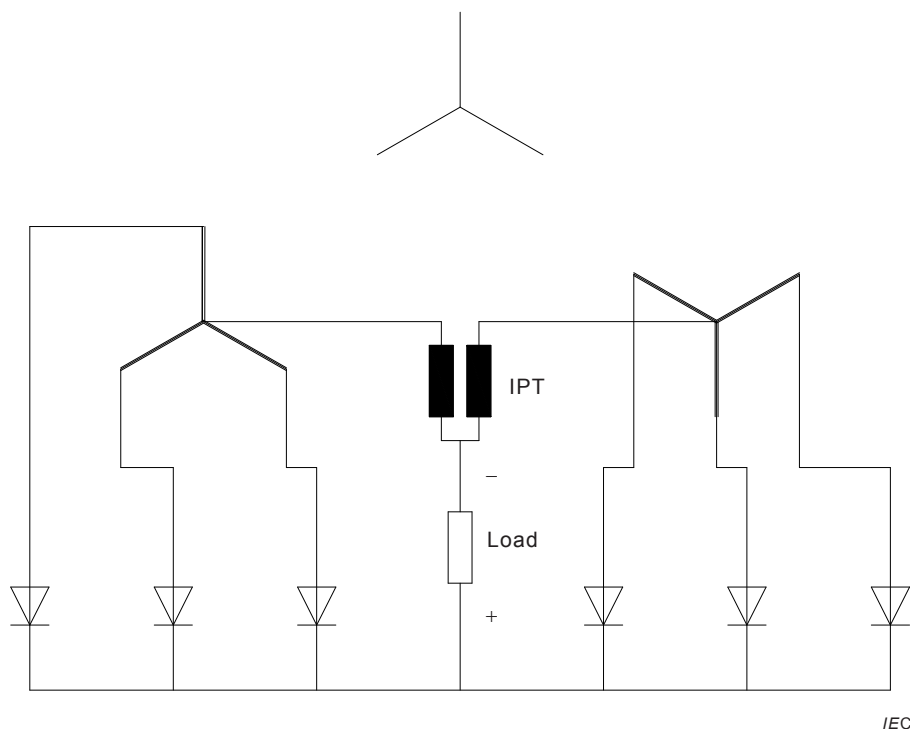


Figure 5 – Double-star connection

The line side is either connected in star or delta and the valve side has two star systems with 180° phase shift. The valve windings should be physically interleaved to avoid DC magnetization of the core and to minimize magnetic leakage fluxes (eddy losses) related to even current harmonics. An interphase transformer (IPT) between the two star points is needed together with a 3 limbs core to ensure 120° valves conduction and to minimize effects of unbalance between the 2 neutral currents of the valve windings. When these 2 neutral currents are balanced, a 5 limbs core may be used instead of the IPT.

The transformer for a six-pulse bridge converter is a three phase unit with the valve windings connected in star or delta.

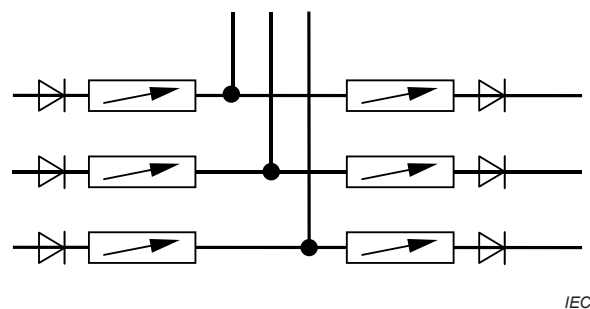
Twelve-pulse reactions can be obtained by using two six-pulse units with different connection groups or by using a transformer with two valve windings, connected in star and delta. This last solution requires a normal three phase core.

More complex cases require a different arrangement with star and delta on the primary side and valve windings connected in star or delta. These particular arrangements may also require a special core design. For 12 pulse double-star rectifiers, phase displacement of 30° needs to be achieved on the line side windings (star – delta, zig-zag, etc.).

Converter plants with more than twelve-pulses require the use of different shifting angles among the various units. This is obtained in most cases by using a zigzag or extended delta connection or more seldom with polygon connection. Detailed description and examples can be found in IEC 61378-1:2011, Annex I.

The physical arrangement of the transformer is preferably done with the valve winding as the outer winding to cater for the simple arrangement of the valve-side exits. The valve-side exit arrangement depends upon the converter structure.

If the converter requires the presence of transducers, they are generally located in the same tank as the transformer and in this case, it is necessary to provide two lead exits by phase. Transducers, if used, may be connected according to Figure 6.



Indicates a transducer

NOTE The symbol of rectifier means either diode or thyristor

Figure 6 – Typical connection of transducers

The physical layout (both inside and outside the tank) of high current busbars may significantly affect the transformer load losses, short circuit impedance and tank hot spots. IEC 61378-1:2011, Annex F gives guidance on how to estimate these effects.

6.2.2 Voltage regulation

In general, there is a need for voltage regulation between the supply and valve voltages and often the regulation range is fairly large from a few percent up to 100 % of the rated valve

winding voltage. The purpose of the wide tapping range is to reduce the consumption of reactive power and harmonic pollution related to converter operation. For practical reasons, the large regulating range often requires a separate regulating transformer between the a.c. terminal and the converter transformer itself.

Depending on the line voltage, the regulating unit can be built either as an autotransformer or with two separate windings to reduce the risks from high transient overvoltages entering the converter transformer.

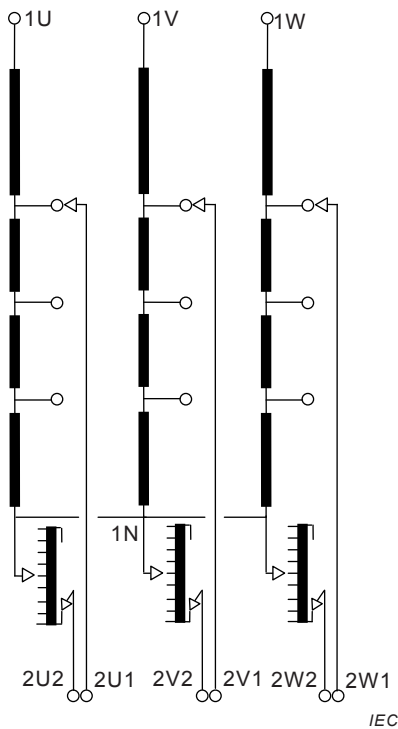
6.2.3 Autotransformer design

6.2.3.1 General

Various common connections are shown in Figures 7 to 13.

6.2.3.2 Star connection – open phases

The schematic constitution of the winding is shown in Figure 7.

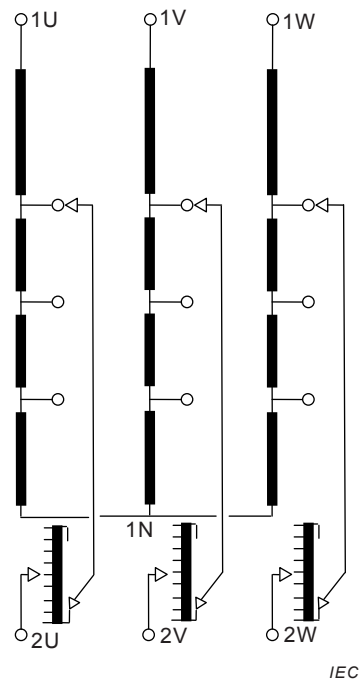


Key

1U – Line	2U1 – Converter transformer	2U2 – Converter transformer
1N – Line neutral	1V – Line	2V1 – Converter transformer
	2V2 – Converter transformer	
1W – Line	2W1 – Converter transformer	2W2 – Converter transformer

Figure 7 – Autotransformer concept for open phases with coarse and fine regulation steps

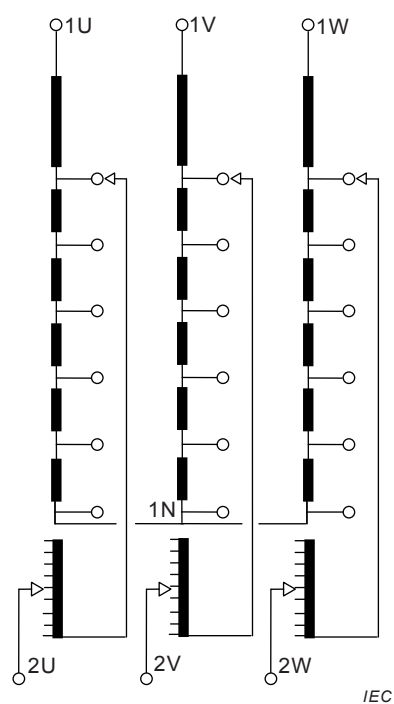
6.2.3.3 Star connection – closed phases



Key

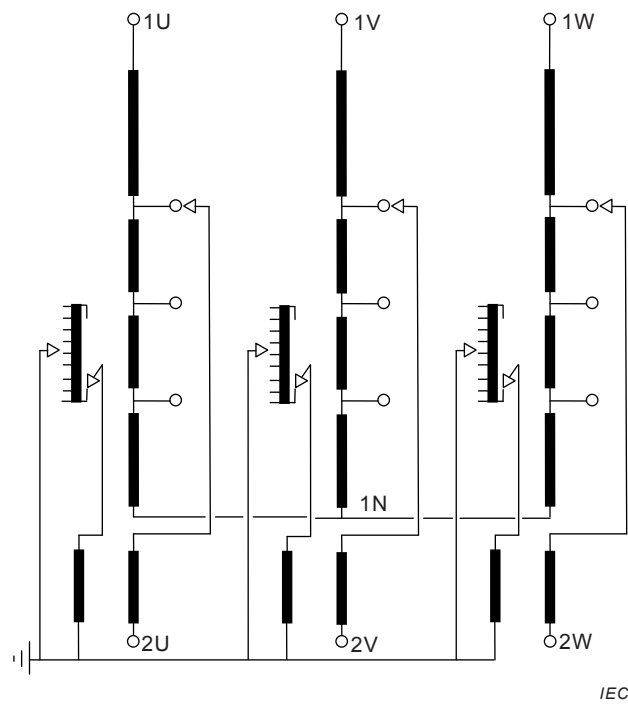
1U – Line	2U – Converter transformer
1N – Line neutral	1V – Line
1W – Line	2V – Converter transformer
	2W – Converter transformer

Figure 8 – Conventional autotransformer concept for closed phases with coarse and fine regulation steps

**Key**

1U – Line	2U – Converter transformer
1N – Line neutral	1V – Line
	2V – Converter transformer
1W – Line	2W – Converter transformer

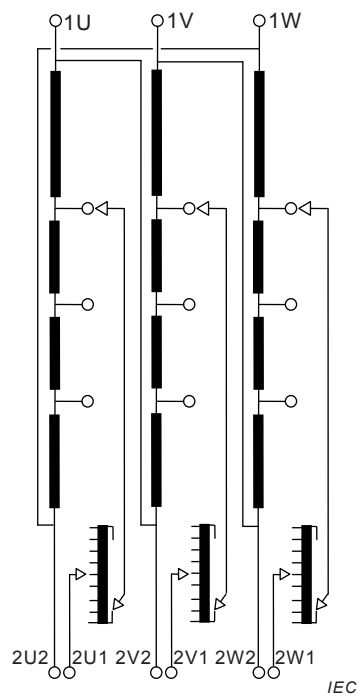
Figure 9 – Conventional autotransformer concept for closed phases with multi coarse regulation

**Key**

1U – Line	2U – Converter transformer
1N – Line neutral	1V – Line
	2V – Converter transformer
	1W – Line
	2W – Converter transformer

Figure 10 – Booster autotransformer concept for closed phases with coarse and fine regulation steps

6.2.3.4 Delta connection – open phases

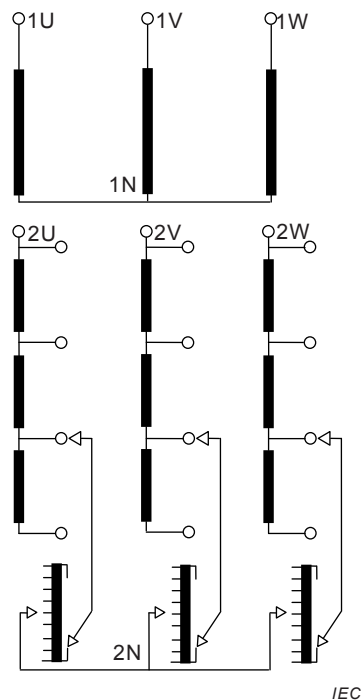


Key

1U – Line	2U1 – Converter transformer	2U2 – Converter transformer
1V – Line	2V1 – Converter transformer	2V2 – Converter transformer
1W – Line	2W1 – Converter transformer	2W2 – Converter transformer

**Figure 11 – Autotransformer concept for open phases
with coarse and fine regulation steps**

6.2.3.5 Two winding design



Key

	1U – Line		2U – Converter transformer
1N – Line neutral	1V – Line	2N – Secondary neutral	2V – Converter transformer
	1W – Line		2W – Converter transformer

Figure 12 – Transformer concept for closed phases with coarse and fine regulation steps

6.3 HVDC applications

6.3.1 Different types of transformer arrangement

In general, HVDC transmissions are built for substantial power ratings with connections to high voltage a.c. systems. In order to reduce the harmonics in the a.c. and d.c. systems the bridges are usually built for twelve-pulse arrangements. Most often the transformers have the windings star-connected on the line side to take advantage of non-uniform insulation requirements and a voltage regulation close to earth. System needs and efficient operation of the converter often require fairly large voltage regulations to be in the range of up to about 40 % of nameplate voltage.

Depending on power rating, voltages and physical constraints, the converter transformers can be built as single phase or three-phase units.

The following solutions are possible to realize HVDC transformers with twelve-pulse bridges.

- Six single-phase, two-winding transformers.
 - Three connected in star/delta.
 - Three connected in star/star.
- Three single-phase, three-winding transformers.
 - All connected star/delta-star.
- Two three-phase transformers.

- One connected star/delta.
 - One connected star/star.
- d) One three-winding transformer.
- Connected star/delta-star.

A converter transformer is generally built with two or three main windings. A tertiary winding is required only in some specific cases, e.g. injection of test voltage, connection to special filter arrangements.

6.3.2 Winding arrangements

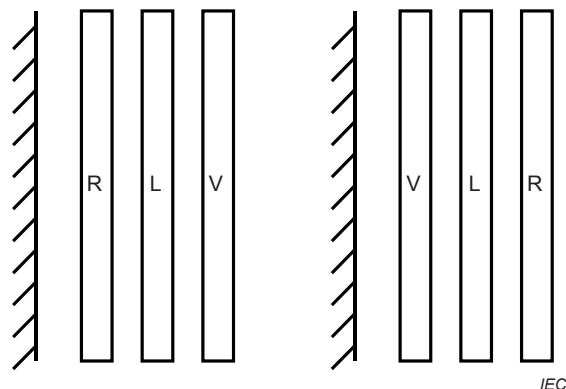
6.3.2.1 General

In core type transformers, the windings are cylinder shaped and arranged concentrically around the core limb. The tapped part of the line-side winding generally forms its own physically separated winding, the regulating winding. The individual windings are almost close to equal height and have equal ampere-turn distribution along the winding height.

In general, the regulating winding is located physically close to the main part of the line winding but not in between valve and the line windings (see Clause 7 for tapping and impedances and Clause 9 for losses).

6.3.2.2 Two windings

In general, there are two ways to arrange the individual windings in a two-winding transformer as indicated in Figure 13. The main and regulating windings form the line-side winding. The valve-side winding consists of one single winding.



Key

R – Regulating (tapping) winding

L – Main (line) winding

V – Valve winding

Figure 13 – Two basic arrangements of the individual windings of a two-winding transformer

Table 1 – Arrangements of two windings

Relative winding position	Advantages	Disadvantages
Regulating – line – valve	d.c. lead exits easy to arrange Regulation by the neutral side	Mechanical realization of lead exits for regulation winding a.c. lead exits Limited solution for regulation winding
Valve – line – regulating	a.c. lead exits easy to arrange Regulation lead exits easy to arrange Regulation by the neutral side	d.c. lead exits more difficult to arrange

6.3.2.3 Three windings

The main solution is as follows.

In single-phase transformer designs, there are generally two wound limbs, one for star/delta and the second one for star/star connections. This means that the valve winding for a delta connection has $\sqrt{3}$ times the number of turns for a star-connected winding but a load current of $1/\sqrt{3}$ of the current in a star-connected winding.

The relative positions of the individual winding shells are the same as the positions for a two-winding transformer (see Table 1).

When the physical size permits for limited power ratings and line voltages, e.g. a medium size back-to-back converter, the transformer may be built as a three-phase, three-winding transformer. Requirements for the impedances to be similar between the line-side terminal and the two valve terminals often require a design with two winding arrangements located axially on the same limb – a so called axial split. The two line-side windings with their regulating windings are connected in parallel and one of the valve windings is connected for delta and the other for star. The relative position of the individual physically separated windings shall be in accordance with Figure 13.

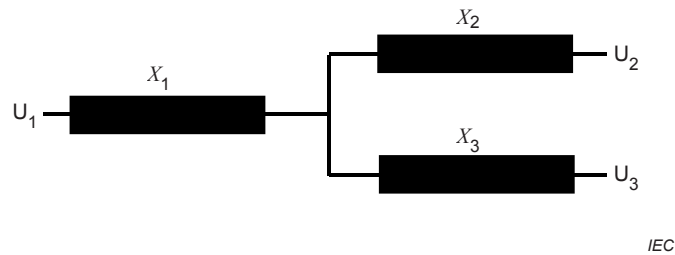
Arrangements where the two valve-side windings each occupy two concentric positions, often on opposite sides of the line winding, are generally not a viable alternative. For a transformer with voltage regulation, it will be difficult to reach the same impedance to the two valve-side windings for all tap positions.

6.3.3 Consideration of impedance – mutual impedance

The impedance pattern between one line and two valve terminals can be visualized by three impedances connected together in one and the same point with two branches towards the two valve terminals and one towards the line terminal, also called the common mutual impedance.

In general, the common mutual impedance shall be as low as possible to avoid interaction between the voltages during commutations.

In two-winding transformers, the common mutual impedance by the transformer is non-existent; contribution to the mutual impedance can only be achieved from the common bus. Three-winding transformers (Figure 14) where the two valve windings are located on different limbs will also have zero mutual impedance. Three-winding transformers using an axial split will also exhibit a low common mutual impedance.

**Key**

$X_1 + X_2 = X_1 + X_3 =$ Transformer impedance

X_1 ideally zero, but always much less than X_2 and X_3

Figure 14 – Mutual impedance

7 Tappings and impedances – HVDC applications

7.1 Value of impedance

The selected impedance is the result of influences from a number of requirements. Although it reduces harmonic current levels, high impedance increases the commutating reactance leading to increased reactive power absorption of the converter, thus increasing the costs of the filter circuit and valve assembly.

Low impedance has an influence on short-circuit force consideration and increases the size and weight of the transformer with consequential effects on cost and transport.

7.2 Variability of impedance

It is essential that the actual and measured transformer impedance remain within a given deviation from a specified value. Deviations may be of systematic as well as random nature.

Systematic deviations may have their origin in design and manufacturing constraints. Random deviations depend on variations in manufacturing and measurement uncertainty. Impedance variations as a function of tap position can be regarded as systematic deviations where the type of tap arrangement influences the course of deviation, e.g. linear or reversing taps.

Permissible impedance deviations from specified values may concern:

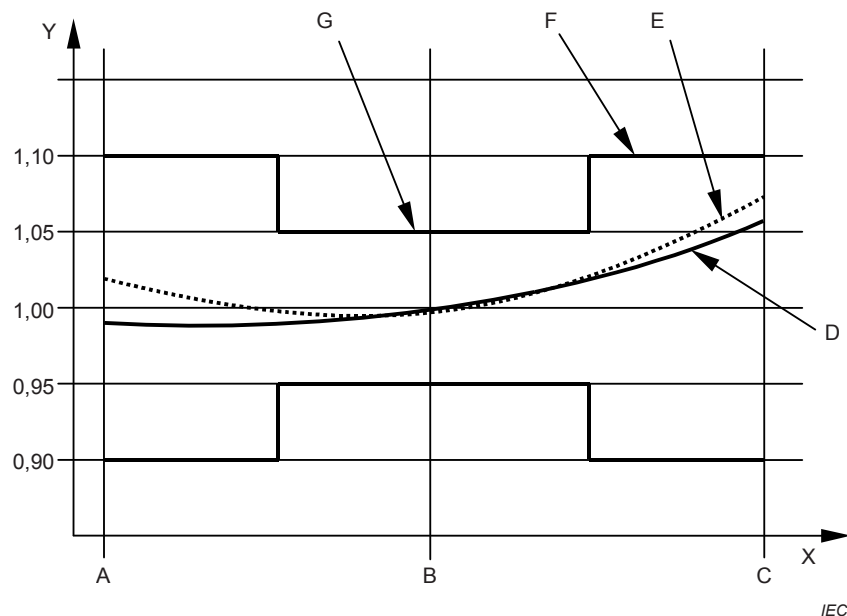
- deviation from a specified impedance value at the principal tap;
- variability between individual phases;
- variability between transformer units;
- variability within the tapping range;
- deviations between star- and delta-connected windings.

The purchaser may specify limits for all five properties.

If not otherwise specified, rules for permissible tolerances laid down in IEC 60076-1 will apply together with the requirements below.

The deviation from the impedance specified by the purchaser shall not exceed 5 % in the usual operating range of tap-changer. Outside this range, the deviation may go up to 10 % (see Figure 15).

The impedance variations between individual phases, transformer units and star- and delta-connected windings should not exceed 3 % for the same tap position. Efficient cancelling of harmonics in a twelve-pulse bridge connection requires small impedance variability. Large variations between phases, units and star- and delta-connected windings will increase the size of the filters.



Key

A – Minimum turns	D – Linear taps	G – $\pm 5\%$ tolerance band
B – Normal turns	E – Reversing taps	X – Turns
C – Maximum turns	F – $\pm 10\%$ tolerance band	Y – Transformer impedance p.u.

Figure 15 – Typical impedance pattern

8 Insulation aspects and dielectric tests

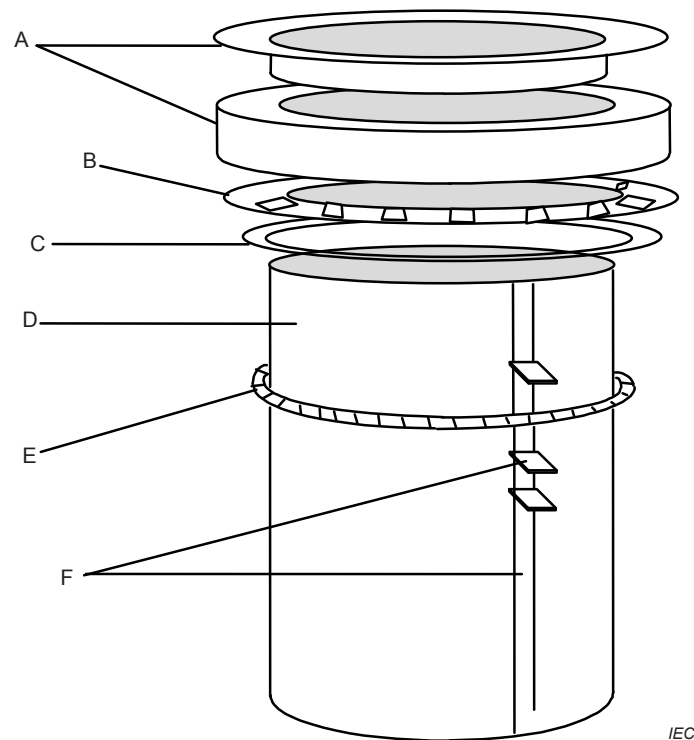
8.1 Hybrid insulation systems

8.1.1 General

Hybrid insulation systems are primarily used in industrial converter transformers since there are advantages of working at elevated temperatures in such transformers.

Whenever the term “hybrid” is used with reference to an insulation system, it means that high-temperature-insulating materials (such as aramide paper or high temperature enamel) are combined with conventional temperature materials (such as cellulose).

Insulating materials are used in several of the different components that make up a transformer's winding: conductor insulation, spacers, cylinders, angle rings, etc. (see Figure 16).

**Key**

A – Angle rings and caps

C – Static rings

E – Conductor insulation

B – Support washer

D – Cylinders

F – Axial and radial spacers

Figure 16 – Components of a typical industrial converter transformer insulating system

For many years, hybrid insulation was applied for oil-cooled transformers. High temperature materials are utilized in parts in direct contact with the copper (conductor insulation) or close to it (spacers), while all the other insulating components consist of cellulose. Windings with hybrid insulation have been designed with an average temperature rise higher than the one allowable for cellulose (without reduction of the transformer life), thus increasing the power per unit of volume.

8.1.2 Hybrid insulation for converter transformers

Whenever a transformer is used in conjunction with a converter, harmonic currents are injected in its windings. The harmonic currents will increase the eddy losses of the windings by a factor defined in IEC 61378-1 and IEC 61378-2. In a conventional transformer, the eddy losses depend on the radial and axial components of the magnetic leakage flux and on the geometric dimensions of the conductor subjected to this flux (see IEC 61378-1). The eddy losses vary along the winding height. They are lower in the central part of the winding where the leakage flux is mostly parallel to the thickness of the conductor and increase at the ends of the winding where the leakage flux is almost perpendicular to the width of the conductor. This non-uniform distribution of losses results in a non-uniform distribution of the temperature along the winding's height. The difference between the hot spot and average winding temperature is therefore increased beyond that caused by the normal cooling mechanism.

In converter transformers, when harmonic currents are taken into account, the difference between the hot spot and the average winding temperature may further increase because of the corresponding increase in eddy losses (see IEC 60076-8:1997, 9.6).

A number of solutions to this problem are available. In agreement with the purchaser, adoption of high-temperature-insulation materials in the hot spot region is a solution whenever