

INTERNATIONAL STANDARD

NORME INTERNATIONALE

**Converter transformers –
Part 3: Application guide**

**Transformateurs de conversion –
Partie 3: Guide d'application**



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INTERNATIONAL STANDARD

NORME INTERNATIONALE

**Converter transformers –
Part 3: Application guide**

**Transformateurs de conversion –
Partie 3: Guide d'application**

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

COMMISSION
ELECTROTECHNIQUE
INTERNATIONALE

ICS 29.180

ISBN 978-2-8322-2233-1

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CONTENTS

FOREWORD.....	6
INTRODUCTION.....	8
0.1 General.....	8
0.2 Rating data (Clause 5)	8
0.3 Winding configurations (Clause 6)	8
0.4 Tappings and impedances (Clause 7)	8
0.5 Insulation aspects and dielectric tests (Clause 8)	9
0.6 Losses (Clause 9)	9
0.7 Core and sound aspects (Clause 10)	9
0.8 Transformer specification (Clause 11).....	9
0.9 Short circuit considerations (Clause 12).....	9
0.10 Components (Clause 13).....	10
0.11 Maintenance (Clause 14).....	10
0.12 Monitoring and on-site investigations (Clause 15)	10
0.13 Additional sources of information	10
1 Scope.....	11
2 Normative references.....	11
3 Terms and definitions	11
4 Symbols and abbreviations	11
5 Rating data.....	12
6 Winding configurations.....	13
6.1 General.....	13
6.2 Industrial applications	15
6.2.1 Rectifier	15
6.2.2 Voltage regulation	16
6.2.3 Autotransformer design	17
6.3 HVDC applications	22
6.3.1 Different types of transformer arrangement.....	22
6.3.2 Winding arrangements	23
6.3.3 Consideration of impedance – mutual impedance	24
7 Tappings and impedances – HVDC applications	25
7.1 Value of impedance.....	25
7.2 Variability of impedance	25
8 Insulation aspects and dielectric tests	26
8.1 Hybrid insulation systems.....	26
8.1.1 General	26
8.1.2 Hybrid insulation for converter transformers.....	27
8.2 Dielectric tests	28
8.2.1 General	28
8.2.2 Dielectric safety margins in long term d.c. and polarity reversal testing	30
8.2.3 Comments on the dielectric test procedures.....	31
9 Losses	33
9.1 General.....	33
9.1.1 General considerations	33
9.1.2 Losses and frequency	34

9.1.3	Current sharing, losses and hot spot in high current windings	35
9.1.4	Current harmonics	35
9.1.5	Transformers with three or more windings wound on the same core limb	36
9.1.6	Dual frequency testing of HVDC transformers	41
9.1.7	Transformers with more than one active part in the same tank	43
9.1.8	Transformers connected to a voltage source converter	44
9.2	Thermal tests	44
9.2.1	General	44
9.2.2	Calculation of test currents and losses for industrial transformers	44
9.2.3	Calculation of losses and test currents for HVDC transformers	44
9.2.4	Considerations on the hot spot and limits of the thermal tests	45
9.2.5	Considerations on temperature rise test of industrial transformers	45
9.2.6	Tank hot spots in industrial transformers	46
10	Core and sound aspects	46
10.1	Core	46
10.1.1	Constructional features	46
10.1.2	Effect of harmonics on transformer active part cores	47
10.1.3	DC bias voltage effect on main active part cores	47
10.1.4	Summary about cores	48
10.2	Sound	48
10.2.1	General	48
10.2.2	Fundamental considerations	49
11	Transformer specification	50
11.1	General	50
11.2	Technical specification versus functional specifications	51
11.2.1	General	51
11.2.2	Technical specifications	51
11.2.3	Functional specifications	51
11.3	HVDC transformer specifications	51
11.4	Notes and comments on specification items to be provided individually by purchaser and supplier	52
11.5	Information to be provided by the purchaser or by the system designer	52
11.5.1	General description	52
11.5.2	System data	52
11.5.3	Environmental data	53
11.5.4	Performance requirements	53
11.5.5	Testing requirements	55
11.5.6	Sequence of factory tests	57
11.5.7	Site tests	57
11.5.8	Design and construction requirements	58
11.5.9	Auxiliary equipment	58
11.5.10	Availability and measures to minimize service downtime	60
11.6	Information to be provided by the supplier	60
11.6.1	General	60
11.6.2	General description	60
11.6.3	Performance data	60
11.6.4	Supplementary data	61
11.7	Quality assurance and test program	63
11.8	Availability and measures to minimize service downtime	

12	Short circuit considerations	63
13	Components	67
13.1	On-load tap-changers	67
13.1.1	General	67
13.1.2	Converters for industrial applications	67
13.1.3	Converter for HVDC applications	68
13.2	Valve-side bushings	68
13.2.1	General	68
13.2.2	Station layout	69
13.2.3	Technical considerations	69
13.2.4	Bushing types	69
13.2.5	Testing	69
14	Maintenance	71
14.1	General	71
14.2	Oil	72
14.2.1	General	72
14.2.2	Oil quality and transformer quality indicators	73
14.3	Insulation quality	73
14.3.1	General	73
14.3.2	Oil sampling requirements	74
14.3.3	Oil tests	75
14.3.4	Oil handling, storage and treatment	76
14.3.5	Oil preservation systems	76
14.4	Tap-changers	77
14.5	Accessories and fittings	79
15	Monitoring	79
15.1	General	79
15.2	Transformer condition assessment in service	80
15.3	Types of monitor	80
15.3.1	General	80
15.3.2	Oil condition monitoring	80
15.3.3	Off-line condition assessment	81
15.3.4	On and off-line monitors	81
15.3.5	Expert systems	83
15.3.6	Fingerprinting	83
15.4	Monitoring summary	84
16	Design review of converter transformers	84
16.1	General	84
16.2	Scheduling and confidentiality	85
16.3	Subject for design review	86
16.3.1	General	86
16.3.2	System information	86
16.3.3	Environmental Information	87
16.3.4	Transformer specific requirements	87
	Bibliography	91

Figure 1 – Bridge connection for six-pulse arrangement..... 14

Figure 2 – Bridge connection for twelve-pulse arrangement	14
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.....	14
Figure 4 – 15° phase shifting is preferably realized by extended delta or zigzag connection.....	15
Figure 5 – Double-star connection.....	15
Figure 6 – Typical connection of transducers.....	16
Figure 7 – Autotransformer concept for open phases with coarse and fine regulation steps	17
Figure 8 – Conventional autotransformer concept for closed phases with coarse and fine regulation steps	18
Figure 9 – Conventional autotransformer concept for closed phases with multi coarse regulation	19
Figure 10 – Booster autotransformer concept for closed phases with coarse and fine regulation steps.....	20
Figure 11 – Autotransformer concept for open phases with coarse and fine regulation steps	21
Figure 12 – Transformer concept for closed phases with coarse and fine regulation steps	22
Figure 13 – Two basic arrangements of the individual windings of a two-winding transformer.....	23
Figure 14 – Mutual impedance	25
Figure 15 – Typical impedance pattern	26
Figure 16 – Components of a typical industrial converter transformer insulating system.....	27
Figure 17 – Insulation system, equivalent R-C circuit.....	29
Figure 18 – Voltage distribution before and immediately after polarity reversal	30
Figure 19 – a.c./d.c. conversion – Simplified sketch.....	32
Figure 20 – Leakage fields for a three-winding transformer with closely coupled valve windings	38
Figure 21 – Leakage fields for a three-winding transformer with decoupled valve windings	39
Figure 22 – Leakage fields for a three winding transformer with loosely coupled double concentric valve windings	40
Figure 23 – Leakage fields for a three winding transformer with loosely coupled double-tier valve windings.....	41
Figure 24 – Short-circuit fault conditions in rectifier bridge	64
Figure 25 – Arrangement of valve bushings	70
Figure 26 – Examples of a.c., d.c. and combined electric field dispositions adjacent to HVDC bushings and associated electric insulation systems	71
Table 1 – Arrangements of two windings	24
Table 2 – Data for calculation of load losses with harmonic currents	43
Table 3 – Monitoring types	82

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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.

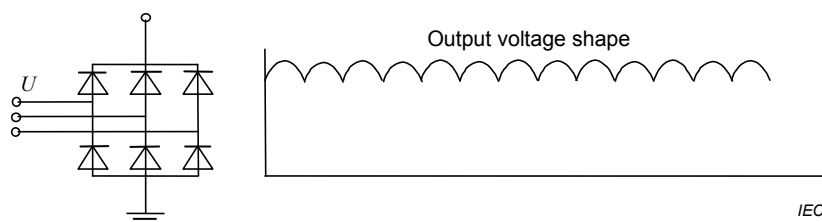
6 Winding configurations

6.1 General

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

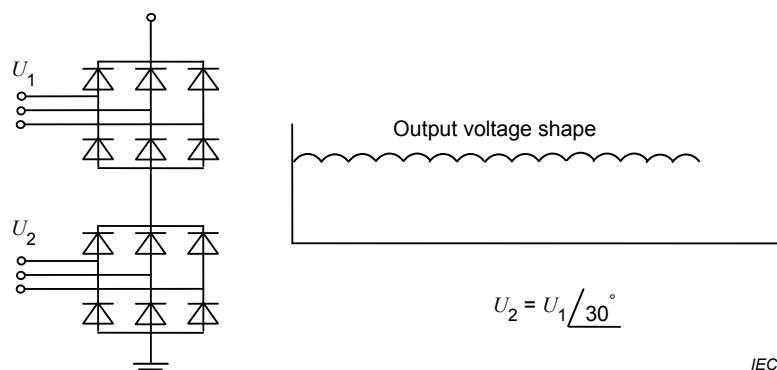
In general, the windings will be arranged to provide a six-pulse converter bridge from a balanced three-phase system. The converter will carry current twice from each phase for a maximum duration of 120 electrical degrees or one third of a cycle, once in positive and once in negative direction. See Figure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

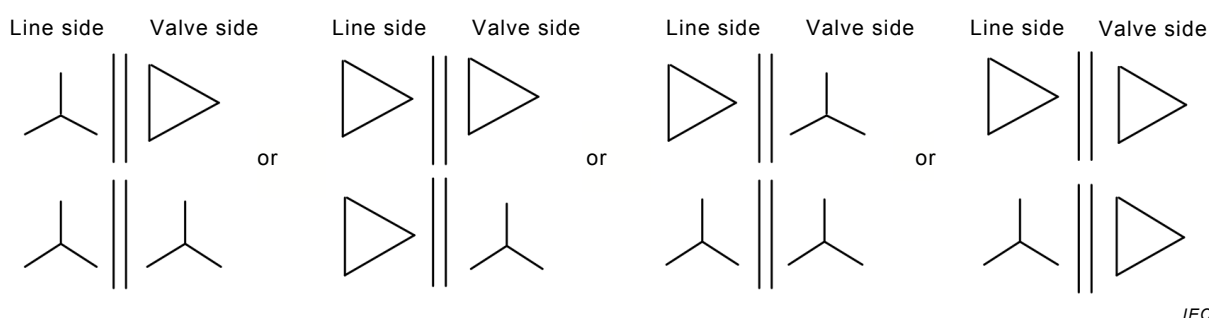


Figure 3 – Transformer connections star-delta and star-star or alternatively, delta-delta and delta-star to give a 30 electrical degree separation between the valve-side voltages

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.

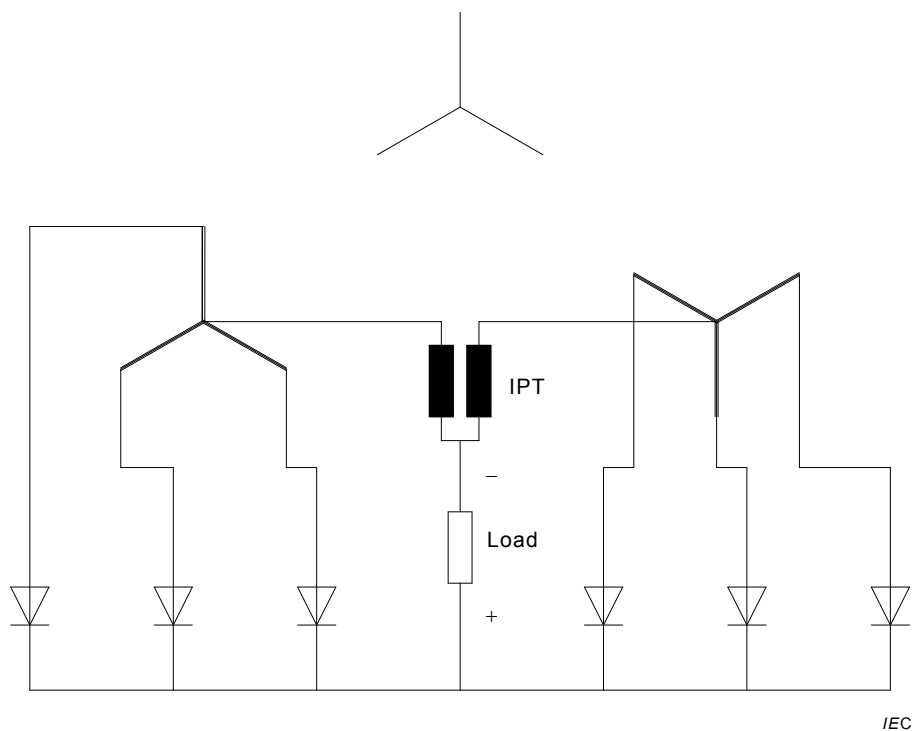


Figure 5 – Double-star connection

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.

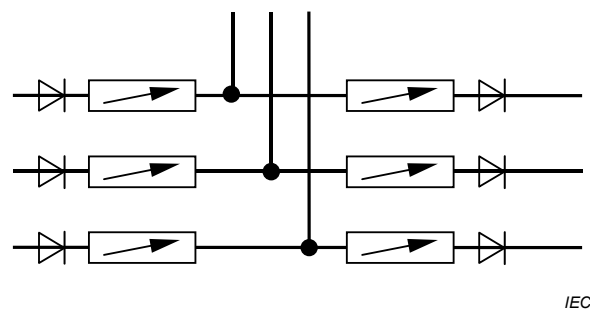
Twelve-pulse reactions can be obtained by using two six-pulse units with different connection groups or by using a transformer with two valve windings, connected in star and delta. This last solution requires a normal three phase core.

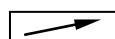
More complex cases require a different arrangement with star and delta on the primary side and valve windings connected in star or delta. These particular arrangements may also require a special core design. For 12 pulse double-star rectifiers, phase displacement of 30° needs to be achieved on the line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

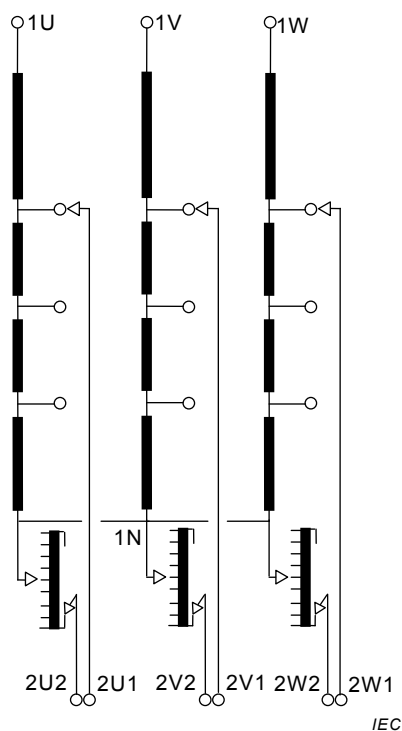
6.2.3 Autotransformer design

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.

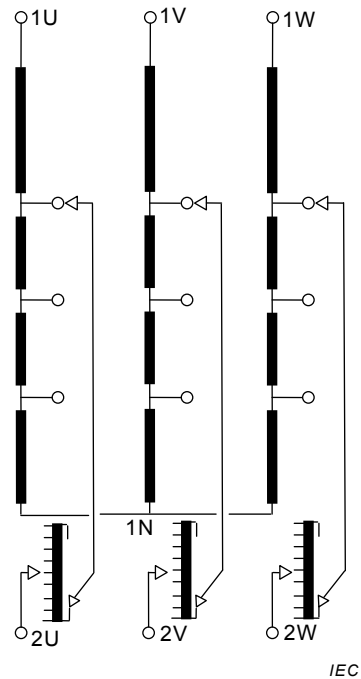


Key

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

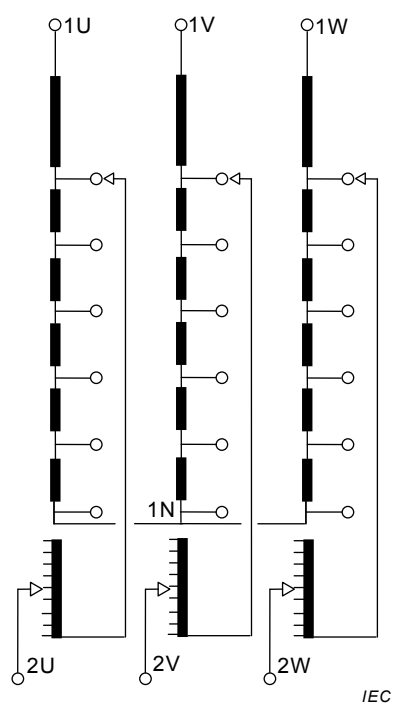
6.2.3.3 Star connection – closed phases



Key

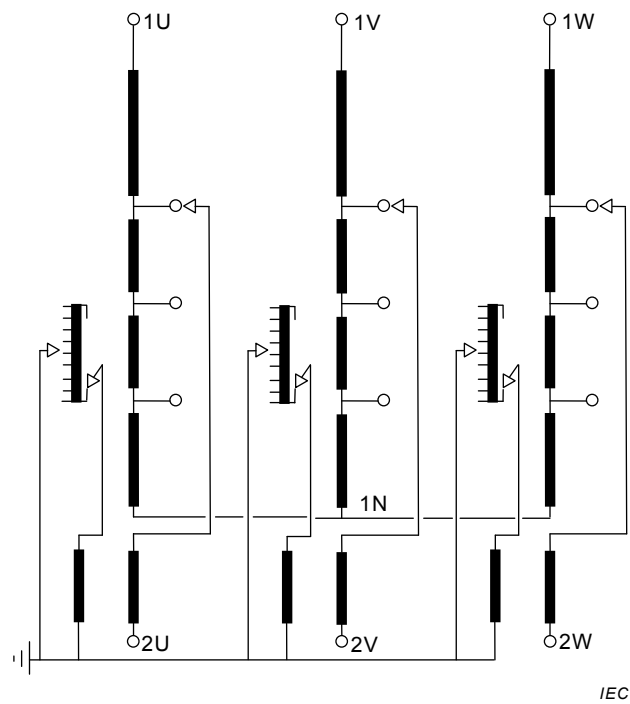
1U – Line	2U – Converter transformer
1N – Line neutral	1V – Line
1W – Line	2V – Converter transformer
	2W – Converter transformer

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

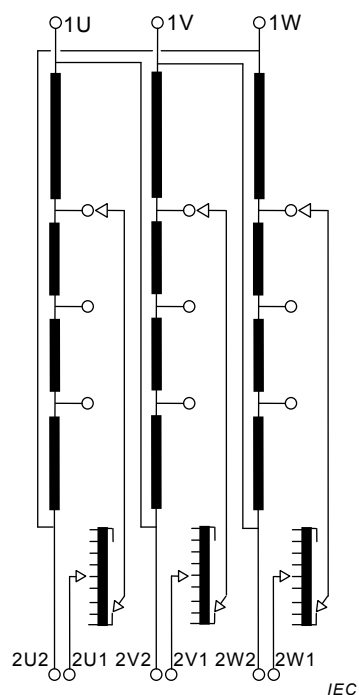


Key

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

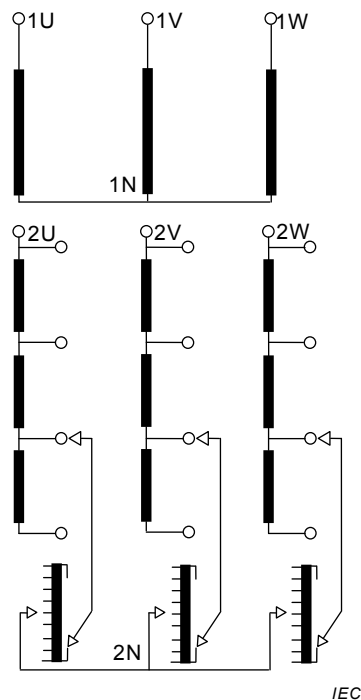


Key

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

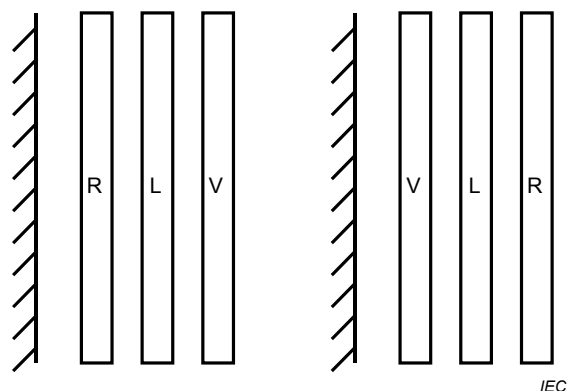
6.3.2.1 General

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.

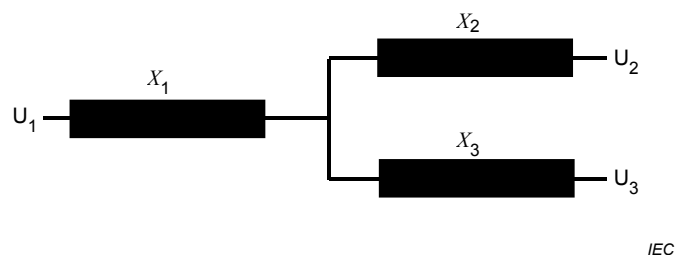
Arrangements where the two valve-side windings each occupy two concentric positions, often on opposite sides of the line winding, are generally not a viable alternative. For a transformer with voltage regulation, it will be difficult to reach the same impedance to the two valve-side windings for all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

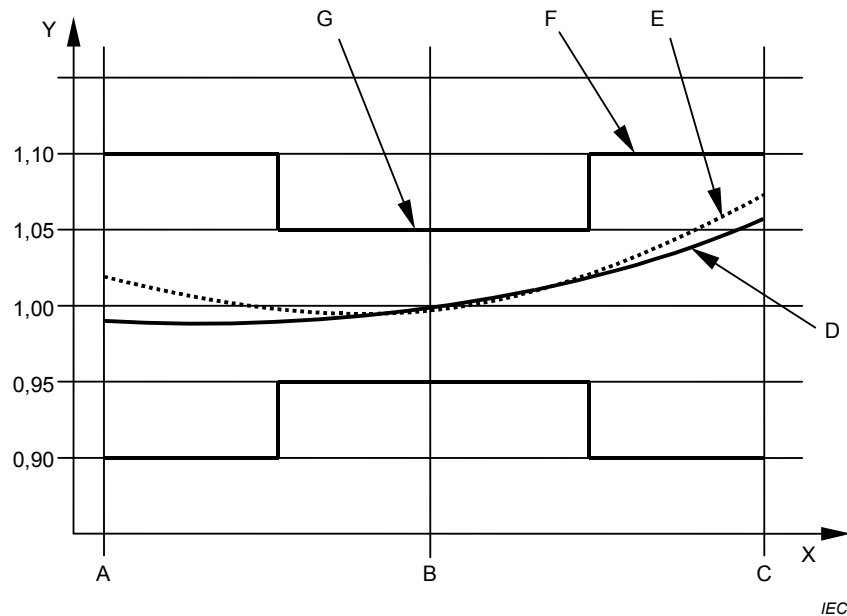
- deviation from a specified impedance value at the principal tap;
- variability between individual phases;
- variability between transformer units;
- variability within the tapping range;
- deviations between star- and delta-connected windings.

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

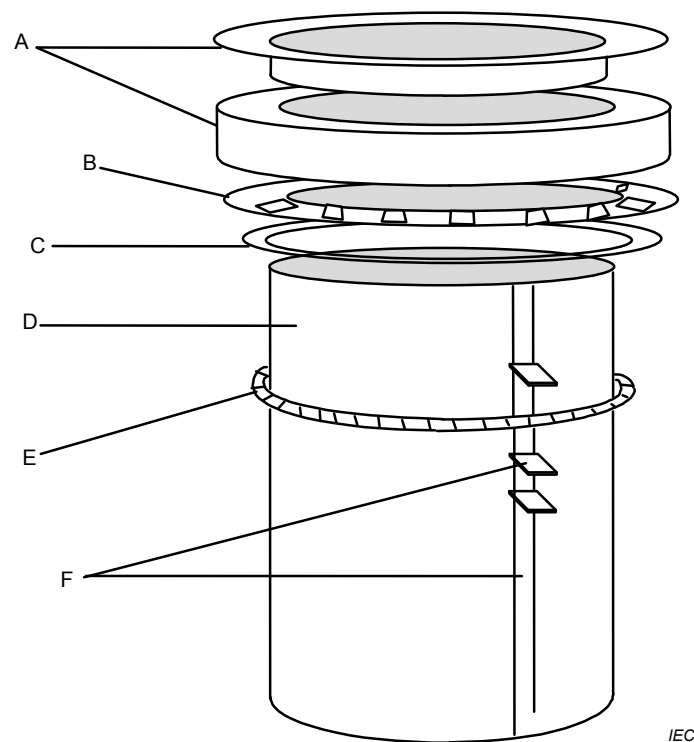
8.1 Hybrid insulation systems

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

it is not possible to reduce the hot spot temperature to limits indicated in IEC 60076-2:2011, 6.2.

In power transformers, hybrid insulation is generally intended to increase the allowable average winding temperature and hence the power rating. Therefore, high temperature insulation material is used near to all the winding conductors. In converter transformers, hybrid insulation could also be used in the areas near to local high hot spot temperatures, while average winding rises remain within limits. It also follows that high-temperature-insulation material should be applied to the winding conductors in the hot spot regions.

More and more solid and liquid high temperature materials are available in the market. This fact increases the number of possible solutions whenever the average and hot spot temperatures are of concern. The correct application of these materials is covered in IEC 60076-14.

8.2 Dielectric tests

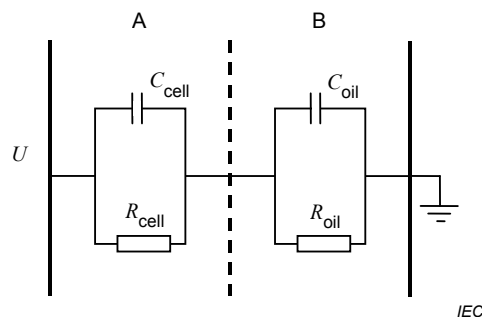
8.2.1 General

Dielectric tests and insulation aspects primarily refer to HVDC converter transformers. The dielectric tests and insulation aspects for industrial converter transformers are identical to those of conventional power transformers and are covered in IEC 60076-3.

The insulation system in a HVDC converter transformer is exposed to the stresses caused by the applied voltage and induced voltages. For the line winding and its terminals, the voltages are of the same nature as for a conventional transformer, that is, steady state a.c. voltages and transitory voltages such as lightning and switching surges. The valve windings and their terminals will in addition to the voltages in a conventional transformer also be subjected to d.c. voltages. This will in turn give rise to a combined a.c. and d.c. stress.

The distribution of all time variable voltages across the insulation system is well defined by the geometry and permittivity of the materials involved. In the following paragraph it is assumed that these materials are mainly transformer oil and cellulose. The distribution of a steady state direct voltage in oil/cellulose insulation deviates significantly from that of time variable voltages (impulse and a.c. voltages). The distribution is mainly governed by apparent resistivities. These resistivities are to a great extent dependent on the mobility of space charges in the insulation system. As a consequence, the resistivity is not a constant value and varies with a number of parameters, such as temperature, electrical stress, moisture, speed of oil flow, duration of voltage application, ageing and chemical structure. These phenomena are better represented by a space-charge time model.

From a practical point of view, it is generally accepted that an insulation structure can be modelled as an R-C network to determine its behaviour under d.c. conditions (provided that ion-drift effect can be neglected). When a d.c. voltage is initially applied, the voltage distribution is capacitive, while the final or steady state d.c. field in a complex structure is determined by the relative resistivities of the involved materials. In most cases, the use of an R-C model gives a conservative and safe design margin. Resistivity ratios between solid insulation and oil may range from 10:1 up to 500:1 at room temperature. As the temperature is increased, the resistivity ratios typically decrease up to one order of magnitude.

**Key**

A – Cellulose

B – Oil

 U – Voltage C – Capacitance R – Resistance**Figure 17 – Insulation system, equivalent R-C circuit**

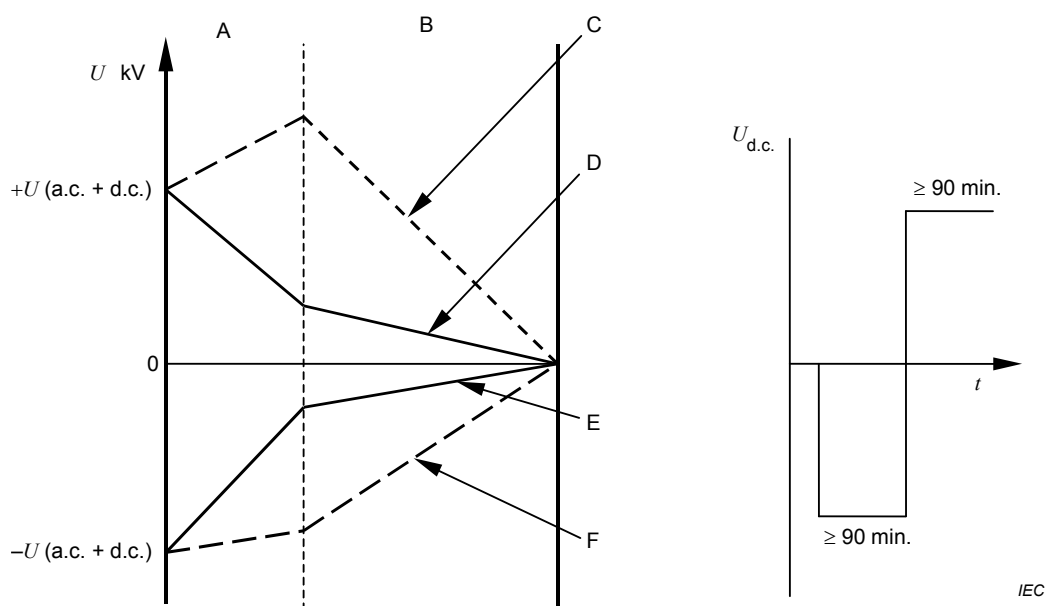
A model shown in Figure 17 can be used to simulate the insulation system. The interface between the oil and the cellulose barrier is assumed to be an equipotential surface.

Because the a.c. and d.c. stresses are predominantly determined by independent parameters, it may be assumed that any complex voltage field can be separated into its a.c. and d.c. components. The stress due to each voltage can be calculated separately, and the two stresses can be combined to give a measure of the actual stress.

Figure 18 gives an indication of the stresses at steady state d.c. voltage and immediately after a polarity reversal, which are the two critical stress patterns. The maximum stresses occur when the resistivity ratio of cellulose/oil is high.

In the steady state condition, a resistive distribution of the d.c. voltage dominates. Normally, the resistivity is such that the major part of the total voltage drop will be across the cellulose. Together with the a.c. component, the distribution in the composite system will be like the lower line in Figure 18. Thus, a significant stress in the solid insulation will develop and this is mainly due to the applied d.c. voltage.

Immediately after a polarity reversal (the upper line in Figure 18), the charge of the cellulose in the opposite direction remains, but will be reduced due to capacitive voltage distribution at the $2U$ step ($-U$ to $+U$). The consequence is a significant increase of the voltage across the oil. The value of resistivities and permittivities involved govern this temporary voltage across the oil. This voltage is normally higher than the voltage across the oil immediately after an application of $+U$ or $-U$, but it will be reduced to a low value (mainly a.c. voltage) in the steady state condition.



Key

A – Cellulose

B – Oil

C – Initial distribution after reversal

D – Final distribution after reversal

E – Final distribution before reversal

F – Initial distribution before reversal

t – Time

U – Voltage

Figure 18 – Voltage distribution before and immediately after polarity reversal

8.2.2 Dielectric safety margins in long term d.c. and polarity reversal testing

Significant variations in resistivity for oil and cellulose, and hence resistivity ratios, will occur during service. This raises the question whether the factory testing represents conditions that demonstrate that there is a sufficient dielectric safety margin for the design.

The aim of the long term d.c. separate source test is to demonstrate that there is a sufficient safety margin over the operating stresses in service across the cellulose insulation. The test is made at room temperature, hence the resistivity ratio between cellulose and oil is comparatively high. This will achieve stresses that are essentially above the most extreme in service. Testing at high temperature will result in a lower safety margin.

The aim of the polarity reversal test is to demonstrate that there is a sufficient safety margin over the operating stresses in service in the oil ducts. However, the duration of the polarity reversal stress under testing conditions is questioned. It has been shown that resistivity ratios close to 1:1 in service may produce stresses in the oil ducts that are not adequately verified by the polarity reversal test. For this reason, a new 1 h separate source a.c. test with partial discharge measurement has been introduced. This test creates a long-term oil duct stress sufficient to demonstrate an adequate safety margin under the worst conditions obtained under polarity reversal in service.

The direct voltage testing shall be carried out at a temperature of $20\text{ °C} \pm 10\text{ °C}$. (see 10.4.3.1 of IEC 61378-2:2001). If the tests are carried out immediately after the heat run test, the time constants for charging and recharging of the insulation system will be shorter due to the high temperature. This may have the effect that the dielectric margins are not demonstrated in a proper way.

Reference is made to 8.2.3 and CIGRE JWG 12/14.10 paper.

The recommendations from the CIGRE paper have been incorporated into the dielectric testing requirements of IEC 61378-2. In summary, IEC 61378-2 incorporates three dielectric tests to validate the d.c. insulation structure of the valve windings:

- long duration d.c. separate source voltage withstand test;
- the polarity reversal test;
- a.c. separate source voltage withstand test.

CIGRE JWG A2/B4.28 has further investigated the effectiveness of PR and DC tests in their present form (see CIGRE Technical Brochures 406 and 407). The key issue is knowledge about oil resistivity.

Such knowledge is vital because:

- steady state stress distribution in the HVDC transformer insulation systems is a function of material conductivities;
- oil resistivity influences the time needed by the insulation system to reach steady state and, therefore, the effectiveness of present tests. Tests duration needs to be longer than the time to reach steady state.

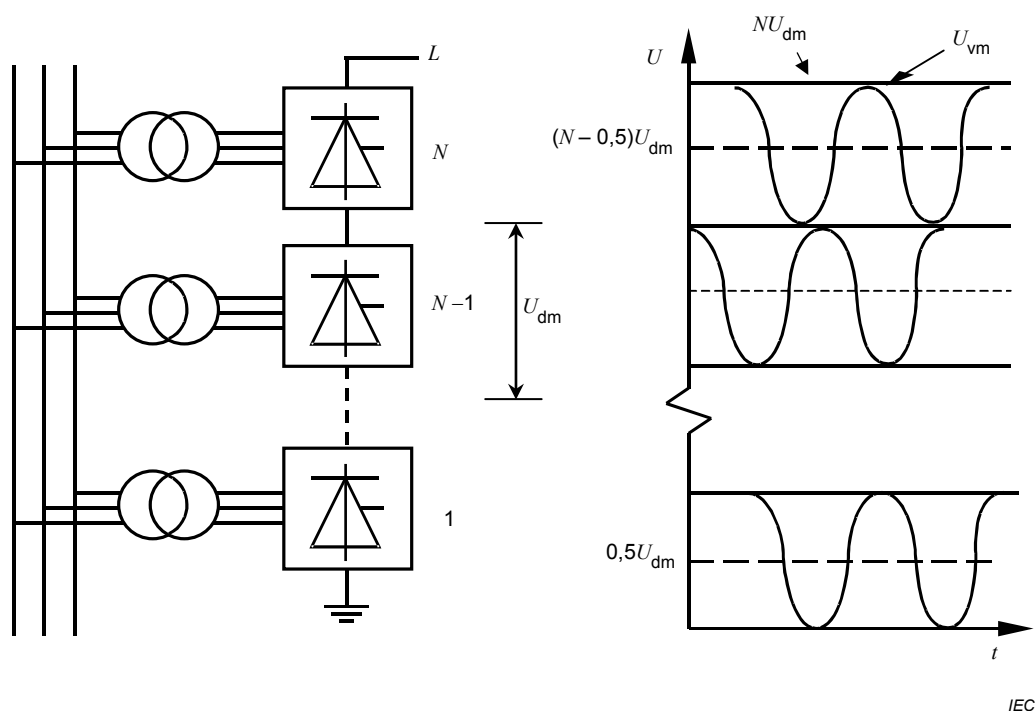
CIGRE JWG A2/B4.28 also determined that oil conductivity is not measured in an uniform and consistent way by HVDC transformer manufacturers and users (see CIGRE Brochure 406).

The matter of oil conductivity has been taken up by CIGRE JWG A2/D1.41 HVDC transformer insulation. Oil conductivity and its results will be reflected in edition 2 of IEC 61378-2.

8.2.3 Comments on the dielectric test procedures

8.2.3.1 General

Figure 19 shows a simplified sketch of the a.c./d.c. conversion scheme and the definition of the voltages U_{vm} and U_{dm} as defined in IEC 61378-2.

**Key** L – Line t – Time**Figure 19 – a.c./d.c. conversion – Simplified sketch****8.2.3.2 DC separate source voltage withstand test**

The test level U_{dc} is expressed in the equation in IEC 61378-2:2001, 8.2.3.

According to Figure 19, the component $(N - 0,5)U_{dm}$ is the direct voltage level of the transformer winding.

The peak value of the superimposed a.c. voltage level is $0,7U_{vm}$. The constant 0,7 is the multiplication factor to obtain this peak value from the a.c. phase-to-phase r.m.s. voltage.

In line with the same procedure used to establish the normal a.c. long-term testing values, the multiplier 1,5 is applied to obtain the test voltage.

8.2.3.3 Polarity reversal test

The test level U_{pr} is expressed in the equation in IEC 61378-2:2001, 8.2.4.

The same principles as mentioned in 8.2.3.2 apply. However, when d.c. with superimposed a.c. is considered, the d.c. component is doubled for the polarity reversal and the a.c. component is added but not doubled. Thus only half of the a.c. component is added, which gives the factor 0,35. The final result is multiplied by 1,25 to give a safety margin.

The polarity reversal is made from positive to negative polarity and *vice-versa*. The reason is that the insulation structure is not perfectly symmetrical and the impact of the transient stresses during the reversal will differ depending on polarity.

8.2.3.4 AC separate source voltage test

The test level U_{ac} is expressed in the equation given in IEC 61378-2:2001, 8.2.5.

The a.c. voltage test level corresponds to the sum of the d.c. voltage level of the valve winding and the peak value of the a.c. phase-to-earth voltage and division by $\sqrt{2}$ gives the r.m.s. value. In line with the procedure of IEC 60076-3 used to establish the normal a.c. long term test value, the multiplier 1,5 is applied to obtain the test voltage.

It should be noted that this test is not a substitute to the polarity reversal test. It is only a supplementary test to be carried out for the reasons described above.

9 Losses

9.1 General

9.1.1 General considerations

Whenever an alternating current flows through the winding of a transformer, in addition to the I^2R losses, it produces:

- eddy losses in windings;
- eddy losses in high current busbars, when present;
- stray losses in structural steel parts.

The external short circuit connection, to be set up for the measurement of the load losses, influences the measuring results. An agreement should be reached between the supplier and purchaser before starting the test on how to correct the measuring results owing to losses and impedances of the test circuit.

When units provided with transducers are subject to load losses tests, the electrical quantities might not be sinusoidal. An agreement should be reached between the supplier and purchaser before starting the test on how to correct the measuring results.

These losses originate as follows.

An a.c. current flowing through a winding produces an alternating magnetic flux. This alternating flux induces electromotive forces in all conductive materials that it encounters. These electromotive forces produce eddy currents in all conductive materials and hence they generate eddy and stray losses.

Electromotive forces are proportional to the derivative of the magnetic flux. If we consider a sinusoidal state, then electromotive forces are proportional to:

$$f \times B$$

where

f is the frequency; and

B is the magnetic flux density.

The magnitude of the induced eddy currents is proportional to:

$$(f \times B)/R$$

where R is the resistance encountered by the eddy currents.

Considering that B is generally proportional to the winding's current I , then the eddy losses are proportional to:

$$(f^2 \times B^2)/R \text{ and therefore } P_{\text{eddy}} = \text{constant} \times (f^2 \times I^2)/R \quad (1)$$

This relationship is also valid for stray losses in structural steel parts, providing they are unsaturated.

9.1.2 Losses and frequency

Eddy currents, induced in a conductive material by an alternating magnetic field, distribute themselves unevenly in the conductor section and concentrate near the conductor surface. This phenomenon is known as "skin effect".

The penetration depth of eddy currents depends on the material, electrical and magnetic properties together with the frequency of the alternating magnetic field. This relationship can be expressed as follows:

$$\text{skin depth} = \frac{1}{\sqrt{\mu \times \pi \times f \times \sigma}} \quad (2)$$

where

μ is the material magnetic permeability;

f is the frequency;

σ is the material electrical conductivity.

The skin effect then influences the value of the conductor resistance at a given frequency. Thus Equation (1) may be rewritten as:

$$P_{\text{eddy}} = \text{constant} \times \frac{f^2 \times I^2}{R(f)} \quad (3)$$

The conductor's resistance remains constant up to a certain frequency (called transition frequency), if the frequency is increased beyond this, the resistance increases in a manner described by the formulae given in Annex A of IEC 61378-1:2011.

Eddy losses in a given conductor will increase with the square of the frequency up to the transition frequency. For higher frequencies, the relationship is:

$$P_{\text{eddy}} \propto f^x \quad (4)$$

where x is $0,5 < x \leq 2$ and constantly decreases with an increase in frequency.

The value of transition frequency of a specific conductor depends significantly on the geometric dimensions of the conductor itself, hence the larger the dimensions, the lower the transition frequency (see IEC 61378-1:2011, Annex A).

The different conductive materials inside the transformer may be divided into two groups:

- winding conductors, the dimensions are usually¹ comparable with the skin depth at fundamental frequency;
- high current busbars and structural steel parts where at least one dimension is significantly greater than the skin depth at fundamental frequency.

The geometric differences between the two groups are reflected in a different relationship between eddy loss and frequency. Eddy losses in winding conductors vary as f^2 , while those in high current busbars and structural steel parts vary as $f^{0,8}$.

The use of just two exponents is a simplification in respect to what is described in IEC 61378-1:2011, Annex A. However, several measurements and simulations have shown that these exponents are both safe and reasonable.

9.1.3 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 (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.

Current values for coils placed at the ends of a valve winding may be typically 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 among 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 should compute:

- I^2R loss due to uneven current sharing among the coils making up the high current winding;
- I^2R loss due to uneven current sharing among the strands making up the turns of each coil;
- 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 subclause 9.1.5).

9.1.4 Current harmonics

The harmonic current will increase the transformer eddy and stray losses. Such increases can reach levels that may lead to transformer failure.

¹ Foil windings are an exception to this (see IEC 61378-1:2011, Annex A Equation (A.4)).

Converters, to which transformers are connected, act as sources of harmonic currents. The characteristic of these harmonics depend on:

- the converter's power circuit configuration;
- the converter's control technique;
- interaction between the converter and the system to which it is applied;
- the characteristic of the power electronic components.

The transformer manufacturer does not have the necessary information and knowledge to predict the current harmonic generated by the converter. Accordingly, IEC 61378-1 and IEC 61378-2 require that a harmonic spectrum be included in the specification in terms of amplitude and phase. 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.

IEC 60146 series identifies different converter power circuit configurations. For each of these configurations, a pulse number p was assigned so that it would be possible to predict the harmonics that, theoretically, should be present.

Current developments in electronics make possible the application of new 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.

9.1.5 Transformers with three or more windings wound on the same core limb

Winding arrangements and leakage fields are described by use of an example of core-form transformers. The same consideration can be applied to shell-form transformers.

In a two-winding transformer, ampere-turns are balanced if the magnetizing current is neglected. 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 interwoven and one line winding;
- b) no coupling – two pairs of valve-line windings separated by an intermediate yoke;
- c) loose coupling :
 - double concentric transformer with one line winding positioned radially between the two valve windings;
 - 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 each other out and do not appear on the line side².

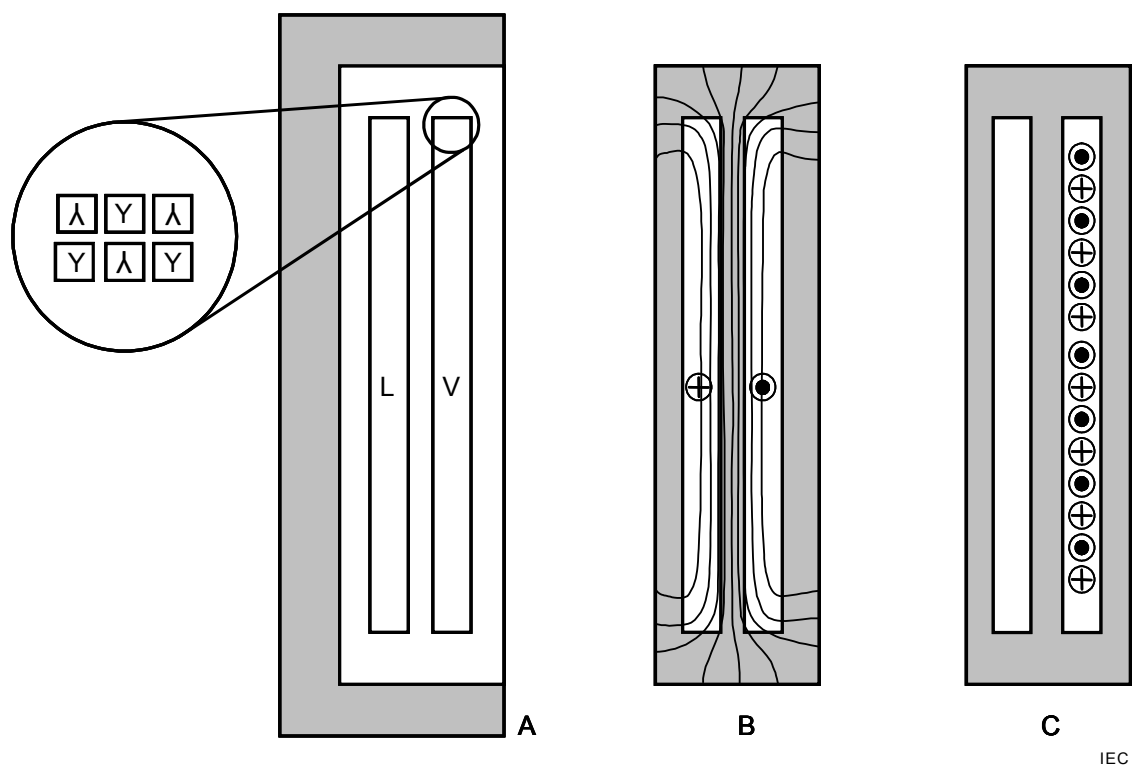
Harmonic currents in phase always contribute to the total eddy loss value.

The effect of harmonic currents in phase opposition is related to the valve winding coupling (see IEC 61378-1:2011, 6.4):

- a) close coupling – harmonics in opposition are balanced between the interwoven valve windings; they produce a negligible leakage flux so that they only produce I^2R losses in the valve windings (see Figure 20);
- b) 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 21);
- c) 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 22);
- d) 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 23). However, local loss distribution may differ significantly, see paragraph below.

When rectifiers cause harmonic currents of opposite direction in loosely connected valve windings, 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 23 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.

² As in even harmonics in a double-star single-way rectifier.



Key

A – Winding arrangement in the core window

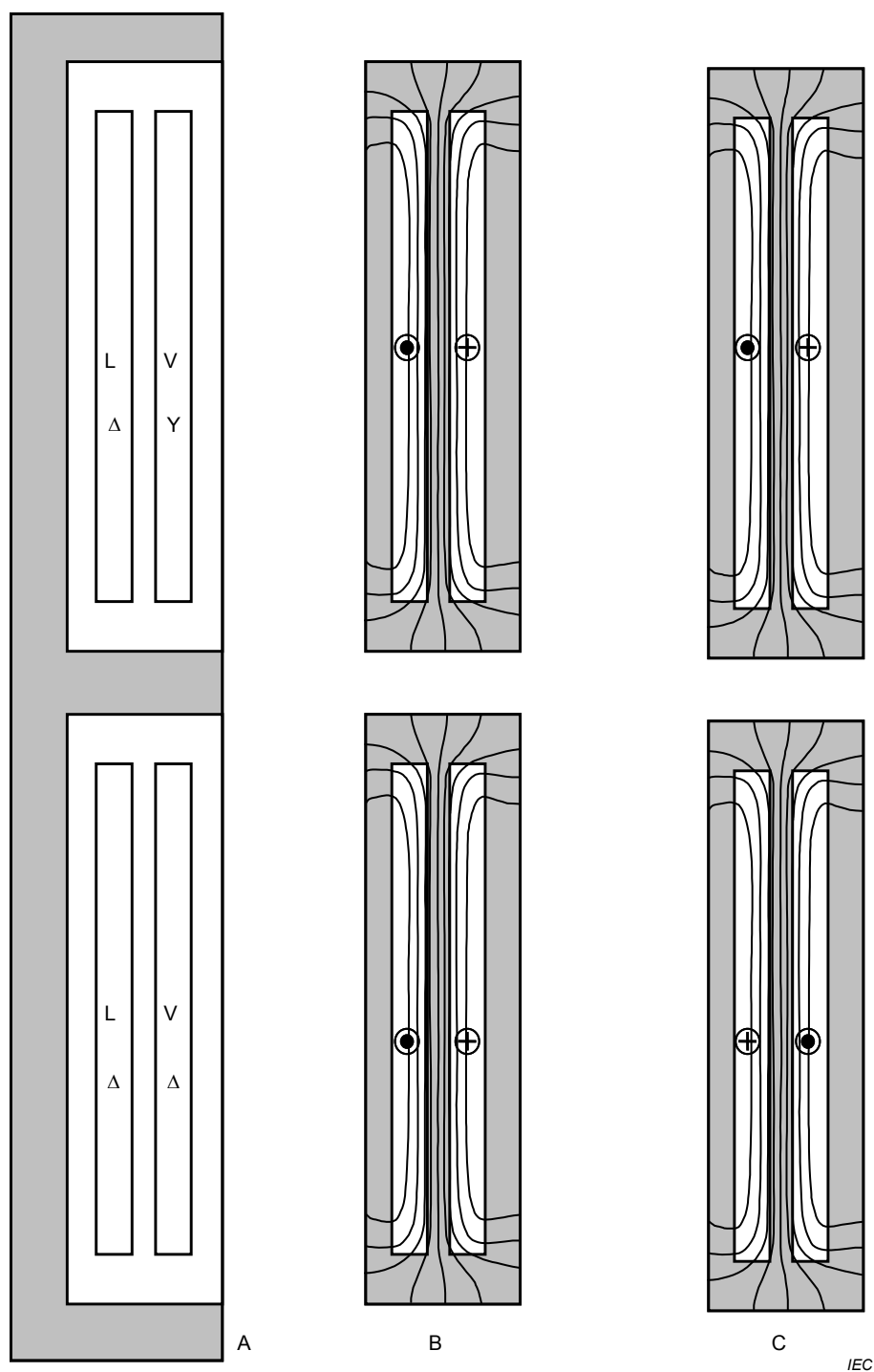
B – Leakage flux produced by harmonics in phase

C – Leakage flux produced by harmonics with 180° phase displacement

L – Line winding

V – Interwoven valve windings

Figure 20 – Leakage fields for a three-winding transformer with closely coupled valve windings

**Key**

A – Winding arrangement in the core window

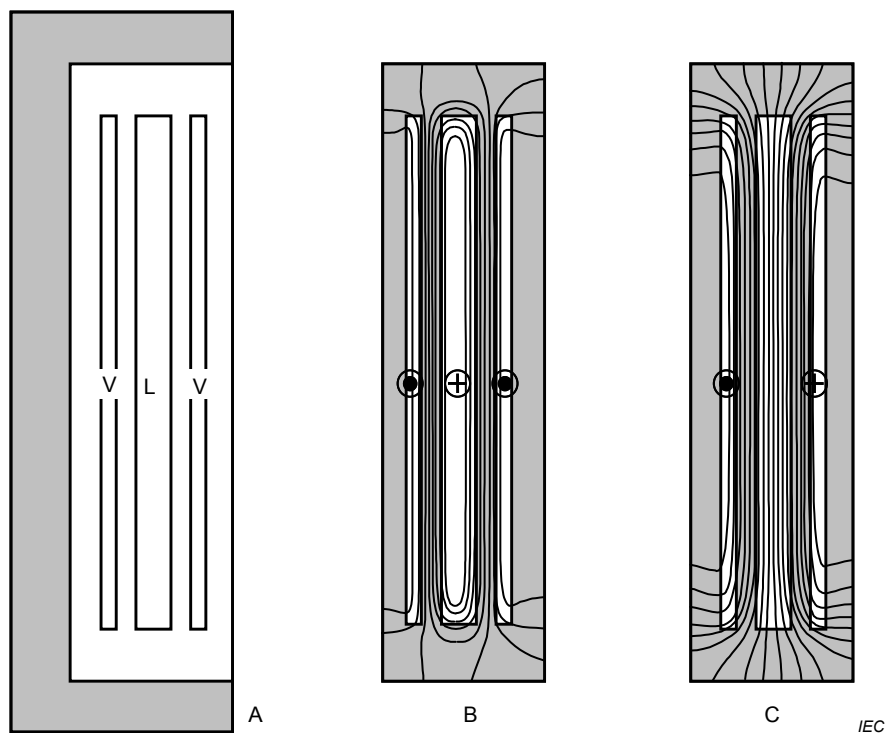
B – Leakage flux produced by harmonics in phase

C – Leakage flux produced by harmonics with 180° phase displacement

L – Line windings

V – Valve windings

Figure 21 – Leakage fields for a three-winding transformer with decoupled valve windings



Key

A – Winding arrangement in the core window

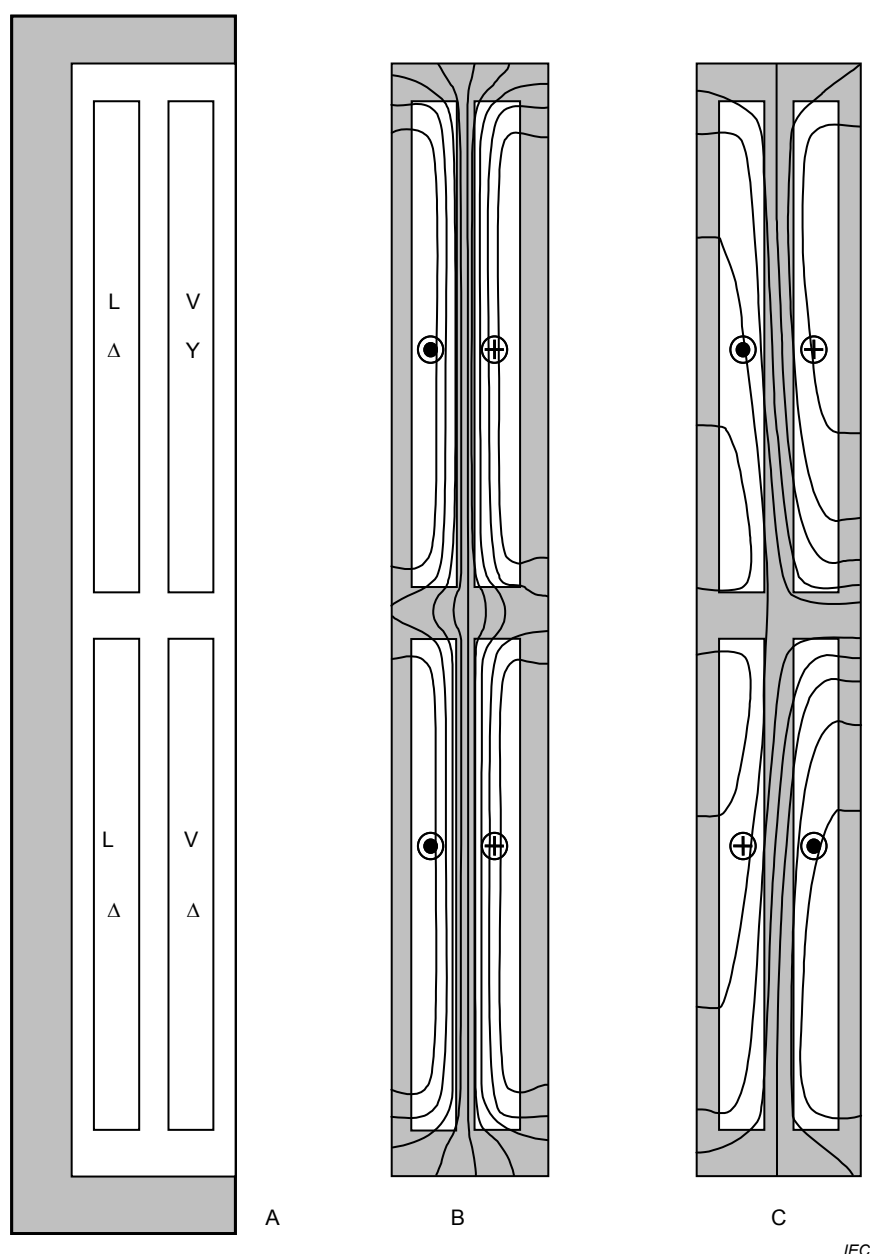
B – Leakage flux produced by harmonics in phase

C – Leakage flux produced by harmonics with 180° phase displacement

L – Line winding

V – Valve windings

Figure 22 – Leakage fields for a three winding transformer with loosely coupled double concentric 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 23 – Leakage fields for a three winding transformer with loosely coupled double-tier valve windings

9.1.6 Dual frequency testing of HVDC transformers

The procedure is based on the difference in behaviour of eddy losses in windings and stray losses in structural parts as described in 9.1.1. Through the measurement at two frequencies it is possible to evaluate the division of eddy and stray losses according the procedure shown in 10.3.2 of IEC 61378-2:2001. Analysis has shown that a reasonable accuracy for the division will be achieved if load loss measurements are made at two different frequencies which are sufficiently separated. If one measurement is made at power frequency (50 Hz or

60 Hz, the second measurement shall be made at a frequency equal to or greater than 150 Hz. A voltage source for the second frequency measurement is normally available since the equipment for induced over-voltage test may be used. This procedure is not intended for use on transformers covered by IEC 61378-1, where a theoretical estimation of the distribution of the eddy losses is made.

The dual frequency procedure implies that:

- the result is based on well-established measurement techniques that lead to a division with reasonable accuracy;
- measurements in the kHz range are avoided;
- theoretical estimation is avoided.

Calculation example:

P_1 is the total load loss at 50 Hz
 P_5 is the total load loss at 250 Hz
 P_{WE1} is the eddy loss in windings at 50 Hz
 P_{SE1} is the stray loss in structural parts at 50 Hz
 $I_{LN}^2 R$ is the ohmic loss at rated current
 I_v is the current at harmonic v
 f is the frequency

Transformer data:

$$P_1 = 449 \text{ kW} \qquad I_{LN}^2 R = 366 \text{ kW} \qquad P_5 = 1\,500 \text{ kW} \qquad (5)$$

giving the following equations:

$$P_1 = I_{LN}^2 R + P_{WE1} + P_{SE1} \qquad (6)$$

$$P_5 = I_{LN}^2 R + P_{WE1} \left(\frac{f_5}{f_1} \right)^2 + P_{SE1} \left(\frac{f_5}{f_1} \right)^{0.8} \qquad (7)$$

Inserting the values gives:

$$449 = 366 + P_{WE1} + P_{SE1} \qquad (8)$$

$$1\,500 = 366 + P_{WE1} \times (250/50)^2 + P_{SE1} \times (250/50)^{0.8} \qquad (9)$$

Solving Equations (4) and (5) gives $P_{WE1} = 39 \text{ kW}$ and $P_{SE1} = 44 \text{ kW}$.

Estimation of service losses:

Harmonic spectrum (see Table 2 below):

Table 2 – Data for calculation of load losses with harmonic currents

$\left(\frac{f_v}{f_1}\right)$	$\left(\frac{I_v}{I_{LN}}\right)$	$\left(\frac{f_v}{f_1}\right)^2$	$\left(\frac{f_v}{f_1}\right)^{0,8}$	$\left(\frac{I_v}{I_{LN}}\right)^2$
1	0,96	1	1	0,92
5	0,18	25	3,62	0,032
7	0,12	49	4,74	0,014
11	0,06	121	6,81	0,003 6
13	0,05	169	7,78	0,002 5
17	0,03	289	9,64	0,000 9
19	0,02	361	10,5	0,000 4

Service losses:

$$P_N = I_{LN}^2 R + P_{WE1} \times \sum_1^v \left(\left(\frac{I_v}{I_{LN}} \right)^2 \times \left(\frac{f_v}{f_1} \right)^2 \right) + P_{SE1} \times \sum_1^v \left(\left(\frac{I_v}{I_{LN}} \right)^2 \times \left(\frac{f_v}{f_1} \right)^{0,8} \right) \quad (10)$$

The equation may be written as:

$$P_N = I_{LN}^2 R + F_{WE} \times P_{WE1} + F_{SE} \times P_{SE1} \quad (11)$$

where F_{WE} and F_{SE} are enhancement factors as described in IEC 61378-2.

Inserting the values gives:

$$P_N = 366 + 39(0,92 \times 1 + 0,032 \times 25 + 0,014 \times 49 + 0,003\,6 \times 121 + 0,002\,5 \times 169 + 0,000\,9 \times 289 + 0,000\,4 \times 361) + 44(0,92 \times 1 + 0,032 \times 3,62 + 0,014 \times 4,74 + 0,003\,6 \times 6,81 + 0,002\,5 \times 7,78 + 0,000\,9 \times 9,64 + 0,000\,4 \times 10,5) = 366 + 3,67 \times 39 + 1,17 \times 44 = 560 \text{ kW} \quad (12)$$

9.1.7 Transformers with more than one active part in the same tank

A converter transformer for industrial applications may, for example, contain in the same tank a regulating autotransformer (connected to the line) that feeds two fixed ratio step-down transformers (connected to the rectifiers).

The valve windings of these two transformers are displaced by 30° and each of them feeds a six-pulse bridge.

Each step-down transformer is subjected to harmonics due to six-pulse operation (harmonic order = $6 \times k \pm 1$, with $k = 1, 2, 3, \dots$).

However, the two six-pulse systems have a 30° displacement in order to give a twelve-pulse operation on the line side. Therefore, the harmonics in the autotransformer are those of 12-pulse operation (harmonic order = $12 \times k \pm 1$, with $k = 1, 2, 3, \dots$).

The eddy losses enhancement factor for the autotransformer windings is then lower than those of the step down transformers because of the cancellation of the 5th and the 7th harmonics.

The stray losses enhancement factors also differ. However, only the sum of the stray losses due to all active parts can be deduced from the measurements.

It is reasonable to assume that each active part produces a portion of the total stray losses that is proportional to the product of its rated power and short-circuit impedance (in p.u.).

Only when the harmonic current spectrum is specified for all the windings in a transformer having more than one active part, is it possible to apply IEC 61378-1 with the modification above for the computation of stray losses enhancement factor.

9.1.8 Transformers connected to a voltage source converter

9.1.8.1 General

It may be possible (by means of filters, commutation strategy and technology) to keep current and/or voltage harmonics within the limits defined by IEC 60076-1:2011, 4.2. However such situation should not be assumed but, instead, verified on a case by case basis.

9.1.8.2 No load losses

In case voltage harmonics exceed the levels defined by IEC 60076-1:2011, 4.2, then it is necessary to properly take into account the additional eddy losses in the core laminations and the increased hysteresis and anomalous losses due to minor BH loops. Hysteresis and anomalous losses are nonlinear phenomena, therefore it is not possible to compute them through harmonic analysis. Such an increase in losses may result in a need to lower the core induction and/or improve the core cooling.

9.1.8.3 Load losses

In case current harmonics exceed the levels defined by IEC 60076-1:2011, 4.2, then the same considerations made for converter transformers connected to line commutated converters should apply.

9.2 Thermal tests

9.2.1 General

The basis of the temperature rise test for converter transformer is to take into account the effect of current harmonics on eddy and stray losses by properly increasing the sinusoidal test loss and current.

9.2.2 Calculation of test currents and losses for industrial transformers

In addition to that already described in IEC 61378-1, it is important to note that, when transformers with more than one active part are considered, the following problems may arise:

- because of harmonic cancellation, one active part may have rated current and F_{WE} significantly lower than the others and this may result in an overload of this active part during the temperature rise test;
- the interconnection of windings belonging to different active parts affects the temperature rise measurement by resistance.

Both problems should be solved by agreement between the transformer manufacturer and the customer at the contract stage.

9.2.3 Calculation of losses and test currents for HVDC transformers

The service load losses are estimated through the procedure described in 9.1.5.

In order to simulate the service load loss during the heat run test, an equivalent load current is used which is derived from the result of the dual frequency measurements.

Taking the calculation example in 9.1.5

Load loss at fundamental frequency: $P_1 = 449 \text{ kW}$ and (13)

Service load loss: $P_N = 560 \text{ kW}$ (14)

From the above, the equivalent test current will be:

$$I_{\text{eq}} = I_1 \times \left(\frac{560}{449} \right)^{0,5} = 1,12 \times I_1 \text{ A} \quad (15)$$

See the equation given in IEC 61378-2:2001, 10.5.

9.2.4 Considerations on the hot spot and limits of the thermal tests

IEC 61378-1 and IEC 61378-2 define the value of an r.m.s. sinusoidal current with power frequency (in a particular winding) that produces the total losses equivalent to that when the winding is harmonically loaded. 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 under harmonically-loaded conditions.

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 as 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 should be a useful tool for checking the thermal behaviour of the unit either during the thermal test, or at on-load service.

9.2.5 Considerations on temperature rise test of industrial transformers

9.2.5.1 Bus bars assemblies to short circuit valve windings during the test

The geometrical and mechanical arrangement of the bus-bars used to short circuit the valve winding will influence:

- the measured load losses and short circuit impedance;
- tank hot spots in the vicinity of the busbars;
- current sharing among busbars connected to the same phase;
- time needed to open up the short circuit at the end of the temperature rise.

The first three points can be addressed by means of 3D magnetic-thermal simulations and the last point by having part of the bus-bars shorted by plates which are held in place by pressure elements (instead of being bolted) so they can be quickly dropped.

9.2.5.2 Transformers with built in transducers

Transducers, during service, are connected in series to diodes and, therefore, they operate with unidirectional currents only. If they are kept in the circuit during load loss and temperature rise tests, then they would operate with bidirectional currents and correspondingly higher core losses. IEC 61378-1:2011, Annex G describes several ways to address this problem.

9.2.5.3 Combined test with rectifier

Sometimes the transformer is tested while connected together with its rectifier.

The assumption is that such combined test is closer (than the individual tests) to real operating conditions.

However, during such combined test, the rectifier is short-circuited. In these conditions, the currents going through the transformer windings will be almost sinusoidal (instead of being close to a square wave when in operation with the real load).

Therefore such combined test is not representative of operating conditions and it is not recommended because:

- it does not allow a more realistic measurement of losses;
- it is not possible to split load losses between the rectifier and the transformer;
- the fact that the valve terminals are connected to the rectifier makes more difficult the measurement of the valve winding temperature rise by resistance method.

9.2.6 Tank hot spots in industrial transformers

Valve windings of industrial transformers carry large currents (from several kA to 100 kA –150 kA).

These currents may cause concentrated hot spots on the tank, which may provoke premature deterioration of gaskets, paint or other adjacent materials.

Once the transformer is built, it is very difficult to apply remedies for these hot spots. This problem is best addressed at design stage by 3D magnetic-thermal simulation (see IEC 61378-1:2011, Annex F).

10 Core and sound aspects

10.1 Core

10.1.1 Constructional features

10.1.1.1 Cores of transformer active part

The design of magnetic circuits is generally the same for converter transformers and conventional a.c. power transformers. Three-phase and single-phase core-form and shell-type constructions may be used, incorporating one of several customary arrangements of yokes and wound and unwound limbs as described in IEC 60076-8.

The type of core and core design are generally decided by the transformer manufacturer. The aim is to achieve the best technical design. However, the core design may also be influenced by the purchaser's specification, for example for reasons of compatibility or interchangeability with existing equipment.

The core materials, limb and yoke configurations, clamping and support structures, core insulation systems, flux control measures, and so forth, usually follow a.c. power transformer technical practices.

10.1.1.2 Cores of transducers when in unit

In rectifier transformers that feed an electrolysis process, often transducers are used for fast and stepless d.c. voltage regulation. These transducers are built by wound laminated core sheets and the transducer control principle requires that the core be magnetised up to full

saturation. This will create significant sound levels due to high magnetostriction forces in the transducer cores themselves.

10.1.1.3 Cores of Interphase transformers when inside the tank

An interphase transformer (IPT) is a special reactor usually connected between the neutrals of both star valve windings of a transformer for single way rectifiers and the d.c. load (see Figure 5).

Interphase transformers are used to optimize parallel operation of line commutated converters, mostly the paralleling of 3 pulse rectifiers. For higher pulses rectifiers (six, twelve, etc.), the impedance of the various circuit components may be enough.

Depending on the interphase transformer type, either 'wound' or 'bar mounted' single core form or shell-type form constructions may be used.

The type of interphase transformer and its type of core and core design is decided by the transformer manufacturer taking into consideration:

- a) the voltage difference between valve windings neutrals;
- b) the direct current rating;
- c) unbalance between neutral currents (which may require the presence of airgaps).

Windings or mounted bars assemblies of interphase transformers are assembled in a way to generate opposing magneto motive forces which cancel each other out when d.c. currents are balanced.

A five limb core for the transformer active part may be an alternative to the use of the interphase transformer, however special care should be taken to minimize any unbalance between the neutral currents.

10.1.2 Effect of harmonics on transformer active part cores

For line commutated converters, when the ratio between the network short circuit power and the power of the converter is big (higher than 10), the line-side voltage is close to sinusoidal. The voltage on the valve side instead, will deviate from sinusoidal by the internal voltage drop in the transformer.

With a sinusoidal voltage, the major magnetic flux will also have a sinusoidal course resulting in no-load loss and magnetizing currents similar to the ones developing in normal a.c. operation. The effect of a d.c. bias current in the line-side and/or valve-side currents are discussed in 10.1.3.

For forced commutated valves, the applied voltage may deviate from a true sinusoidal shape and the harmonics in voltage will have an influence on the harmonic content of the magnetic flux which has to be considered by taking into account the different components of no load losses (eddy losses, hysteresis and anomalous losses in core laminations)

10.1.3 DC bias voltage effect on main active part cores

A small d.c. bias current circulating in the valve winding(s) may have its origin from several different sources. Slight differences in the valve operation can give rise to small residual currents of d.c.-nature through the valve winding(s). Differences in potential between line-side neutral and the earthing point for star connected line-side windings will result in a d.c.-bias in the line winding. Such potential differences may have their origin in adjacent current carrying the earthing point of the d.c. system, e.g. a system with earth return.

The d.c.-bias will have an influence on the magnetic flux as an unipolar component. Steps are taken so that such unipolar component is kept small enough to avoid significant effects on the no-load loss.

A d.c.-bias will also increase sound level from single-sided saturation of the core lamination (see IEC 60076-10-1).

10.1.4 Summary about cores

For HVDC units, the dominant difference for the core between converter operation and conventional a.c.-operation is that it is subject to a d.c.-bias current, which needs to be minimized at system level.

For industrial units, the dominant difference regarding cores between converter operation and conventional a.c.-operation can be the presence of:

- transducers which pose challenges to testing under a.c. conditions;
- interphase transformers which cannot operate (and therefore tested) without being connected to a converter.

10.2 Sound

10.2.1 General

It is increasingly required that equipment sound levels in service should not attain values that exceed acceptable environmental levels.

In practice, these levels are usually imposed by governmental and other statutory authorities. They usually apply to the overall converter station and not to the individual plant items. The sound levels may refer to one or several measurement points around the periphery of the installation, normally the boundary.

Therefore, when an overall sound level is prescribed for a converter station, a sound level value shall be derived for each transformer in addition to the other individual plant items. The value obtained will represent the transformer maximum permissible sound level allowed in service.

Unlike conventional power transformers in a.c. operation, the sound level of converter transformers depends on the following.

- In operation, a converter transformer may be subject to a wide range of harmonic voltages and currents of various magnitudes, in addition to a d.c. bias voltage and current.
- Whenever present, transducers and/or interphase transformers are the main source of noise in converter transformers. Different design solutions of interphase transformers cores can have a significant effect on noise generation (however there are no means to quantify with precision such effects). The same consideration is not applicable to transducers which need to work in saturated conditions.
- In specifying a maximum permissible overall site sound level, there is the dual problem of determining the actual permissible contribution from a transformer and proving this value will not or has not been exceeded.

At present, there is no standard test procedure for determining the on-load sound characteristic of a converter transformer at site for comparison with a specified site sound-limiting value.

The present standard practice for HVDC transformers is for purchasers to specify a measured sound level that will be obtained in the factory during a rated no-load test at the fundamental frequency.