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INTERNATIONAL STANDARD

Bushings for DC application

IEC/IEEE 65700-19-03:2014-07(en)

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IEC Central Office
3, rue de Varembé
CH-1211 Geneva 20
Switzerland
Tel.: +41 22 919 02 11
Fax: +41 22 919 03 00
info@iec.ch
www.iec.ch

Institute of Electrical and Electronics Engineers, Inc.
3 Park Avenue
New York, NY 10016-5997
United States of America
stds.ipr@ieee.org
www.ieee.org

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INTERNATIONAL STANDARD

Bushings for DC application

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

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BUSHINGS FOR DC APPLICATION

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This International Standard has been prepared by a joint working group of sub-committee 36A: Insulated bushings, of IEC technical committee 36: Insulators and Bushing subcommittee of the IEEE-PES transformer committee[1].

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

FDIS	Report on voting
36A/173/FDIS	36A/174/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.

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

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- withdrawn,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

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

1 A list of IEEE participants can be found at the following URL: <http://standards.ieee.org/downloads/65700/65700-19-03-2014/65700-19-03-2014_wg-participants.pdf>.

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INTRODUCTION

In this first edition of IEC/IEEE 65700-19-03, service experiences as well as established market requirements have been harmonized with existing IEC and IEEE standards, primarily:

IEC 60137, *Insulated bushings for alternating voltages above 1 000 V*

IEC 62199, *Bushings for DC application*

IEEE Std C57.19.00™, *IEEE Standard General Requirements and Test Procedures for Outdoor Power Apparatus Bushings*

IEEE Std C57.19.03™, *IEEE Standard Requirements, Terminology and Test Code for Bushings for DC Application*

This dual numbered standard replaces the previous IEC and IEEE DC bushing standards.

Where applicable, reference is also made to the following standards:

IEC 61462, *Composite insulators – Hollow insulators for use in outdoor and indoor electrical equipment*; and

IEC 62155, *Hollow pressurized and unpressurized ceramic and glass insulators for use in electrical equipment with rated voltages greater than 1 000 V*.

Non-ceramic bushing insulators are widely used in DC applications and this standard applies to similar qualification procedures on all types of insulators, except for the artificial pollution test. Preparation of a bushing for an artificial pollution test destroys the surface of a composite insulator and therefore cannot be performed on such bushings.

The range of type tests and routine tests has been carefully planned, considering that high voltage direct current (HVDC) power transmission is a mature technology, but still with limited service experience compared to AC systems and voltage coordination may vary with different system HVDC design practices.

Work on IEEE Std C57.19.03 edition 1 was started in 1988 within the Working Group on Bushings for DC Applications of the Bushing Subcommittee of the IEEE Transformers Committee. The working group decided to address requirements for these bushings in a self-standing document because many problems specific to this type of bushing were being experienced within the industry and other available standards on bushings were inadequate for this purpose. The main reference for the resulting document was its counterpart for ac bushings, IEEE Std C57.19.00-1991 and IEC 60137. Requirements were also coordinated with the CIGRE Joint Working Group 12/14.10 as well as with the HVDC Converter Transformer and Smoothing Reactor Subcommittee of the IEEE Transformers Committee, which developed standards for these HVDC apparatus during the same time frame.

IEEE Std C57.19.03:1996 was approved by the IEEE-SA Standards Board on 20 June 1996 and published on 6 January 1997. During the reaffirmation process for this document in 2002, several errors in the document were reported. All known errors were corrected in a corrigendum in December 2005. This revised standard includes the corrections made in the corrigendum.

Work on IEC 62199 started in 2000 by IEC SC 36A, the insulated bushings subcommittee of IEC TC 36, the insulators technical committee, and was largely based on IEEE Std C57.19.03. Edition 1 was published in 2004.

After work on the revision of IEEE Std C57.19.03 was started by IEEE it was agreed at a meeting of IEC TC36 in Sao Paulo in 2008 to approach IEEE to establish a Joint Maintenance Team under the Dual Logo Standard procedure. This was agreed and work on the new document IEC/IEEE 65700-19-03 was started in 2009.

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BUSHINGS FOR DC APPLICATION

1 Scope

This International Standard applies to outdoor and indoor bushings of any voltage used on DC systems, of capacitance graded or gas insulated types for use as components of oil-filled converter transformers and smoothing reactors, as well as air-to-air DC bushings. This standard does not apply to the following:

- cable terminations (potheads);
- bushings for instrument transformers;
- bushings for test power supplies;
- bushings applied with gaseous insulation (other than air at atmospheric pressure) external to the bushing;
- bushings for industrial application;
- bushings for traction application;
- bushings for distribution class transformers.

This standard makes reference to IEC 60137 for general terms and conditions and defines the special terms used, operating conditions, ratings, test procedures as well as general mechanical and electrical requirements for bushings for DC application.

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 60050, *International Electrotechnical Vocabulary (IEV).* Available from: http://www.electropedia.org/

IEC 60060-1:2010, *High-voltage test techniques – Part 1: General definitions and test requirements*

IEC 60071-1, *Insulation co-ordination – Part 1: Definitions, principles and rules*

IEC 60071-5, *Insulation co-ordination – Part 5: Procedures for high-voltage direct current (HVDC) converter stations*

IEC 60076-1, *Power Transformers – Part 1: General*

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

IEC 60076-7, *Power Transformers – Part 7: Loading guide for oil-immersed power transformers*

IEC 60137:2008, *Insulated bushings for alternating voltages above 1000 V*

IEC 60270, *High-voltage test techniques – Partial discharge measurements*

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

IEC 60376, *Specification of technical grade sulfur hexafluoride (SF6) for use in electrical equipment*

IEC 60480, *Guidelines for the checking and treatment of sulfur hexafluoride (SF6) taken from electrical equipment and specification for its re-use*

IEC 60836, *Specifications for unused silicone insulating liquids for electrotechnical purposes*

IEC 60867, *Insulating liquids - Specifications for unused liquids based on synthetic aromatic hydrocarbons*

IEC 61245, *Artificial pollution tests on high-voltage insulators to be used on d.c. systems*

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

IEC 61462, *Composite hollow insulators – Pressurized and unpressurized insulators for use in electrical equipment with rated voltage greater than 1 000 V – Definitions, test methods, acceptance criteria and design recommendations*

IEC 62155, *Hollow pressurized and unpressurized ceramic and glass insulators for use in electrical equipment with rated voltages greater than 1 000 V*

CISPR 16-1 (all parts), *Specification for radio disturbance and immunity measuring apparatus and methods*

CISPR 18-2, *Radio interference characteristics of overhead power lines and high-voltage equipment – Parts 2: Methods of measurement and procedure for determining limits*

IEEE Std C57.19.00™-2004, *IEEE General Requirements and Test Procedures for Outdoor Apparatus Bushings (ANSI)*

IEEE Standards Dictionary Online[2]

3 Terms, definitions and symbols

3.1 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 60137, IEEE Std C57.19.00, IEC 60050-471 and the IEEE Standards Dictionary Online, as well as the following, apply.

3.1.1
DC bushing
bushing subject to DC voltage stress, i.e. bushings applied to the valve winding side of a converter transformer, bushings applied to a DC smoothing reactor, wall bushing or a bushing applied to a converter valve

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3.1.2
bushing for pure DC application
DC bushing subject to a DC voltage with only a small AC voltage ripple, such as applied on the high voltage side of a DC converter valve

3.1.3
bushing for combined voltage application
DC bushing subject to a large AC voltage superimposed on a DC bias voltage, such as a bushing applied to the valve winding side of a converter transformer

3.1.4
wall bushing
roof bushing
bushing intended to be mounted on the wall (roof) of a building such as a converter valve hall

3.1.5
tilted bushing
bushing intended to be mounted at an angle of 20° to 70° from the vertical

3.1.6
vertical bushing
bushing intended to be mounted vertically or at an angle not exceeding 20° from the vertical

3.1.7
horizontal bushing
bushing intended to be mounted horizontally or at an angle 70° to 90° from the vertical

3.1.8
draw-lead bushing
bushing that will allow use of a draw-lead conductor

3.1.9
draw-lead conductor
cable or solid conductor that has one end connected to the transformer or reactor winding and the other end drawn through the central tube of the bushing and connected to the top of the bushing

3.1.10
major insulation
insulation material providing the dielectric, which is necessary to maintain proper isolation between the energised conductor and ground potential, consisting of internal insulation and the insulation envelope(s)

3.1.11
internal insulation
Insulating material provided in a radial direction around the energised conductor in order to insulate it from the ground potential

3.1.12
charging current
capacitive current
current resulting from charge absorbed by the capacitor formed by the capacitance of the bushing

3.1.13
dissipation factor
tangent of the dielectric loss angle

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Note 1 to entry: For small values of dielectric loss, the dissipation factor is virtually equal to the insulation power factor.

3.1.14
insulation power factor
ratio of the power dissipated in the insulation, in watts, to the product of the effective voltage and current in volt-amperes, when tested under a sinusoidal voltage and prescribed conditions

Note 1 to entry: The insulation power factor is equal to the cosine of the phase angle between the voltage and the resulting current when both the voltage and current are sinusoidal.

3.1.15
partial discharge
discharge that does not completely bridge the insulation between electrodes

Note 1 to entry: The term corona is preferably reserved for partial discharge in air around a conductor, but not within the bushing assembly.

3.1.16
corona
external partial discharge due to ionisation of the air surrounding a conductor caused by a voltage gradient exceeding a critical value

3.1.17
radio-interference voltage
RIV
high-frequency voltage generated as a result of partial discharge or corona, which may be propagated by conduction, induction, radiation or a combined effect of all three

3.1.18
polarity
polarity of the DC voltage with respect to ground, for example positive or negative

3.1.19
polarity reversal
change of voltage polarity from positive to negative or from negative to positive polarity

3.1.20
insulating barriers
set of barriers which form part of the insulation structure of the converter transformer or smoothing reactor at the oil end of the DC bushing

Note 1 to entry: Usually supplied for DC systems of nominal voltage above 150 kV.

3.1.21
leakage current
conduction current
current resulting from the resistance of the dielectric insulation and surface leakage

3.2 List of variables

$I_{\mathrm{eq,DC}}$ is the total equivalent (or test) DC current;

I_h is the magnitude of the h^{th} harmonic current in the transformer;

$I_{\mathrm{test,AC}}$ is the applied fundamental frequency AC current during the thermal test;

R_{AC} is the resistance of the current carrying parts of the bushing under test at fundamental (or test) frequency;

R_{DC} is the DC resistance of the load current carrying part of the bushing under test;

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R_h is the AC resistance of the load current carrying part of the bushing at the h^{th} harmonic;

U_1 is the rated voltage (see 4.1.1 and 4.1.2);

U_{AC} is the AC r.m.s. test voltage for measurement of partial discharge;

U_{dm} is the highest DC voltage per valve bridge;

U_{DC} is the DC withstand test voltage;

U_{pr} is the polarity reversal test voltage (DC voltage);

U_{vm} is the maximum phase-to-phase AC operating voltage of the valve windings of the converter transformer on which the bushing will be assembled. The parameter also applies to wall bushings installed on the ac-side of the converter valve;

N is the number of six-pulse bridges in series from the neutral of the DC line to the rectifier bridge connected to the bushing when mounted on the converter transformer. The parameter also applies to wall bushings installed on the ac-side of the converter valve.

4 Ratings

4.1 Rated voltages

4.1.1 Rated continuous DC voltage

The rated continuous DC voltage is the maximum continuous DC voltage assigned to the bushing by the manufacturer for specified operating conditions.

4.1.2 Rated peak voltage

The rated peak voltage is the maximum value of the combination of DC voltage plus peak AC voltage that the bushing is required to withstand under the specified operating conditions.

4.2 Insulation levels

According to IEC 60071-5 the insulation levels for bushings used in DC applications do not generally follow the standard values of insulation level given in IEC 60071-1. The purchaser shall specify the insulation levels. The methods of calculation for test voltages are given in the relevant clauses of this standard.

4.3 Rated currents

The definition of rated current depends on the bushing application. If the bushing is one for pure DC application, the ratings are defined in 4.3.1. If the bushing is one for combined voltage application, the ratings are defined in 4.3.2.

4.3.1 Pure DC applications

4.3.1.1 Rated continuous DC current

The rated continuous DC current is the maximum continuous direct current that the bushing is required to carry under the specified operating conditions.

4.3.1.2 Rated DC overload current

The rated DC overload current is the maximum direct current that the bushing is required to carry for a stated duration of time and ambient temperature. The purchaser shall specify the current magnitude, duration and frequency of occurrence.

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4.3.2 Combined voltage applications

In these applications, the bushing is usually required to carry AC current.

4.3.2.1 Rated continuous AC current

The rated continuous AC current is the r.m.s. equivalent of the actual current wave shape (including fundamental and harmonic frequency components) that the bushing is required to carry based on the DC rated load current commutated with zero commutating reactance.

$$I_{\text{v}} = I_{\text{d}} \cdot \sqrt{\frac{2}{3}} \approx I_{\text{d}} \cdot 0{,}816 \qquad (1)$$

where

I_{v} is the r.m.s. value of the AC side current;

I_{d} is the DC side current.

Based on zero overlap angle at zero commutating reactance.

4.3.2.2 Rated AC overload current

The rated AC overload current is the maximum alternating current that the bushing is required to carry for a stated duration of time and ambient temperature. It shall be the r.m.s. equivalent of the actual current waveshape that the bushing is required to carry based on the DC rated overload current commutated with zero commutating reactance.

4.3.2.3 Rated momentary (short-time) current

The rated momentary short-time current is the current flowing through the bushing at the major peak of the maximum cycle as determined from the envelope of the current wave. This current is expressed as the root mean-square value including the DC component. Duration of momentary current shall be 1 s unless otherwise specified.

4.4 Rated frequency

Rated frequency is the frequency of the AC system to which the bushing is connected. Rated frequency for bushings for pure DC application is “DC”.

4.5 Pollution parameters

The purchaser shall specify the minimum creepage distance or the minimum USCD (see IEC 60815-1) or, alternatively, the degree of pollution severity.

The necessary creepage distance may be determined from the USCD by:

$$C \times U_1 \times k_{\text{d}} \qquad (2)$$

where

C is the minimum nominal unified specific creepage distance (USCD), see IEC 60050-471:2007, 471-01-16;

k_{d} is the correction factor depending on the average diameter of the bushing.

U_1 is the rated continuous dc voltage or the r.m.s. value of the combined dc and ac phase to earth voltage, depending on the point of application of the bushing in the electrical scheme (kV);

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For combined voltages:

$$U_1 = \sqrt{\left(\left((N - 0{,}5) \times U_{\text{dm}}\right)^2 + \left(\frac{U_{\text{vm}}}{\sqrt{3}}\right)^2\right)} \quad (3)$$

For indoor bushings, the minimum USCD value shall be 17 mm/kV.

If artificial pollution tests are required, they shall be performed in accordance with 10.1.

NOTE Values for USCD and k_d for outdoor bushings are under consideration by IEC TC 36: Insulators.

5 Operating conditions

5.1 General

Bushings conforming to this standard shall, unless otherwise stated, be suitable for operation at rated values under conditions defined in IEC 60137 and summarized as follows:

a) The ambient air temperature is within the limits specified in Table 1

b) Altitude does not exceed 1 000 m.

c) The temperature of the transformer insulating oil in which the oil end of the bushing is immersed is within the limits specified in Table 1.

d) The temperatures and temperature rises of external connections and metal parts in contact with insulating materials do not exceed the limits given in Table 2 of IEC 60137:2008.

e) No moisture condensation is present on the outer surface of the indoor part of outdoor-indoor bushings, indoor bushings and indoor-immersed bushings.

Table 1 – Temperature of ambient air and immersion media (see 5.1)

Subject	Temperature °C
Ambient air:	
– maximum outdoors	40
– maximum indoors (valve hall)	[a]
– maximum daily mean (open air)	30
– maximum daily mean (air-insulated ducting)	70
– maximum annual mean	20
– minimum indoors (valve hall)	5
– minimum outdoor	-30
Oil in transformers:	
– maximum	
• for rated power	100
• for long time emergency duty [b]	115
– maximum daily mean	90[d]
Other media:	
(gaseous and non-gaseous)	[c]

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NOTE 1 The daily mean temperature of the immersion medium should be calculated by averaging 24 consecutive hourly readings.

NOTE 2 By agreement between purchaser and supplier, other temperature ranges may be adopted.

[a] maximum valve hall temperature shall be specified for each specific project and that the maximum valve hall ambient temperature is normally ranging from 40 °C to 60 °C depending of the technology used.

[b] The values for oil in transformers are in accordance with IEC 60076-1 and IEC 60076-2. The value for emergency duty is in accordance with IEC 60076-7.

[c] In the absence of other information, reference should be made in principle to the corresponding IEC apparatus standard for which the bushing is intended, whereby particular attention should be paid to bushings one end of which is to be immersed in gas.

[d] Where a maximum daily mean temperature of 95 °C is specified I accordance with IEEE Std C57.19.00, the bushing temperature rise shall be reduced appropriately.

5.2 Factors affecting the design, testing and application

Where particular operating conditions exist, they shall be specified by the purchaser.

Examples of such conditions are as follows:

a) The ambient air temperature, for bushings operating wholly or partially in the valve hall. It is common to have a maximum HVDC valve hall air temperature well over the standardised 40 °C maximum air temperature. Values up to 60 °C are of usual practice. Such high ambient air temperatures have significant effects on dielectric withstand as well as maximum operating temperature. If a valve hall air ambient temperature exceeding 40 °C is specified care should be taken regarding dielectric withstand performance as well as maximum operating temperature.
b) Surface creepage distance may be achieved using shed material of porcelain, silicone rubber or other materials. Where silicone rubber is used the selection and amount of fillers may have a large impact on the useful life. The type of shed profile such as anti-fog or long-short (ratio 0,7) may improve voltage withstand conditions over even or uniform shed design
c) Inclination.
d) Seismic loading.
e) Vibrations or shocks.
f) Transportation or storage conditions.
g) Other thermal conditions.
h) Damaging fumes or vapours, excessively abrasive or conducting dusts, explosive mixtures of dust or gases, salt spray, icing, etc.
i) Proximity of insulating barriers or earthed walls within the transformer or reactor.
j) Proximity of the walls or roof of a building.
k) Ice loading conditions.
l) Overloads.

5.3 Altitude correction

Although the insulation level refers to sea level, bushings corresponding to this standard are declared suitable for operation at any altitude not exceeding 1 000 m. In order to ensure that the external withstand voltages of the bushing are sufficient at altitudes exceeding 1 000 m, the arcing distance normally required shall be increased by a suitable amount. It is not necessary to adjust the radial thickness of insulation or the clearance of the immersed end. The puncture strength and the flashover voltage in the immersion medium of a bushing are not affected by altitude.

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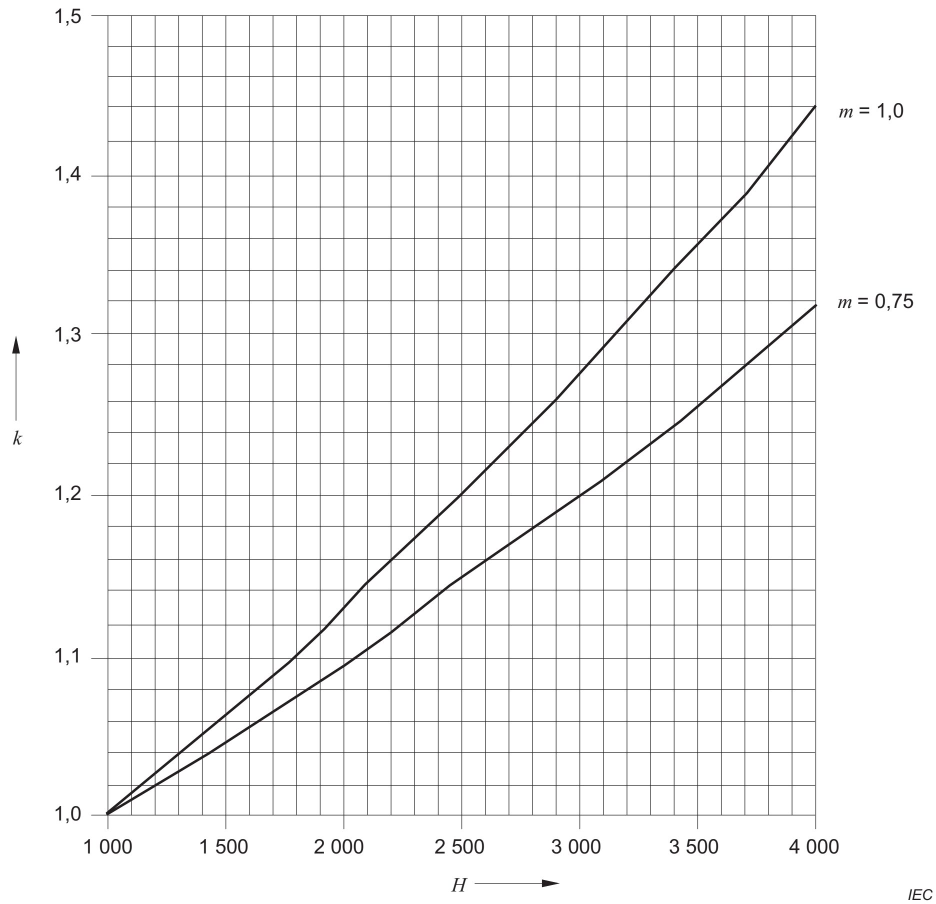
For installations at an altitude higher than 1 000 m, the arcing distance under the standard reference atmospheric conditions shall be determined in order to withstand the voltages obtained by multiplying the withstand voltages required at the service location by a factor k in accordance with Figure 1.



These factors are calculated with the following equation:

$k = e^{m(H-1\,000)/8\,150}$

where

H is the altitude (m);

m = 1 for the power frequency and lightning impulse voltage;

m = 0,75 for the switching impulse voltage.

NOTE Limited information is available for altitude correction under DC conditions. A factor m = 1 is considered conservative.

Figure 1 – Altitude correction factor

Owing to the limitations of puncture strength and flashover voltage in the immersion medium, it may not always be possible to check the adequacy of the increased arcing distance by actual tests at any altitude lower than that of operation. In such a case the supplier shall demonstrate that arcing distance of the bushing is adequate.

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5.4 Interchangeability

DC bushings in converter transformers and smoothing reactors are not normally interchangeable with other DC bushings of the same voltage and current. This is because the condenser foil arrangement must align properly with the insulating barriers to minimise voltage stresses. This may not apply to DC bushings without insulating barriers.

6 General requirements

6.1 Electrical requirements

- Voltage withstand tests
- Partial discharge
- Dissipation factor and capacitance
- Bushing voltage tap. Capacitance graded bushings may be provided with a voltage tap. This tap is normally intended for use as a voltage divider during normal operation and may require the use of additional capacitance to limit the output voltage and protective devices. These additional components may be mounted directly to the bushing or in the transformer control cubicle.
- Bushing test tap. Capacitance graded bushings may be provided with a bushing test tap. This tap is normally grounded and is intended for measurement of dissipation factor, capacitance from conductor to tap, and partial discharge. Since the capacitance from tap to ground is not controlled, the tap is not intended for use as a voltage divider during normal operation. Bushing test tap functionalities may be integrated in voltage tap.
- When not in use the voltage tap and test tap shall be effectively grounded throughout the life of the bushing
- Creepage distance

6.2 Mechanical requirements

- Dimensions
- Cantilever strength
- Internal pressure and vacuum
- Apparatus bushings shall be designed to withstand full vacuum when mounted in the apparatus tank
- Draw lead bushing cap pressure

The liquid or gas for internal insulation of the bushing shall comply with their relevant material standards:

- IEC 60376 for new SF_6 or IEC 60480 for used SF_6.
- IEC 60296 for oil, or
- IEC 60836 or IEC 60867 for synthetic fluid.

6.3 Nameplate markings

The following information shall appear on all bushing nameplates:

- Manufacturer's name, identification number, type, year of manufacture and serial number.
- Rated continuous DC voltage (for bushings for pure DC application, see 4.1.1).
- Rated peak voltage (for bushings for combined voltage applications, see 4.1.2).
- Rated continuous DC current, where applicable.
- Rated continuous AC current, where applicable.

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- Dry lightning impulse voltage withstand.
- Dry/wet switching impulse voltage withstand or dry power-frequency voltage withstand.
- Capacitance, C_1 and C_2, on all bushings equipped with voltage taps, and C_1 on all bushings equipped with test taps.
- Dissipation factor measured from conductor to tap, where applicable.
- Type of insulating gas, and minimum pressure, where applicable.
- Mass if greater than 100 kg.
- Maximum angle of mounting if exceeding 30° from vertical.

7 Test requirements

7.1 General requirements

The tests shall be made in accordance with Clause 7 of IEC 60137:2008 (Test requirements), except where described differently below. Where applicable, reference shall also be made to IEC 61378-2, IEC 61462 and to IEC 62155.

- Most of the dielectric routine and type tests can be carried out with the bushing axis at any inclination, regardless of its intended service angle where appropriate.
- The wet switching impulse voltage withstand test and the thermal, mechanical and special tests shall be carried out with the bushing mounted at its intended service angle, unless other arrangements have been agreed and if shown compatible and sufficient.
- DC tests on converter transformer and reactor bushings shall be carried out with external insulation (barriers) and ground planes surrounding the lower end of the bushing in a position as similar as possible to that of the intended service condition. The simulation of the insulation arrangement may be agreed between the manufacturer and the purchaser.
- In cases where a bushing is exposed to DC applied voltage withstand and Polarity Reversal tests and it is tested with a temporary insulating barrier system in oil, it is recommended that the conductivity and fibre content of the oil are recorded.
- DC tests on wall (roof) bushings shall be carried out with wall ground plane and mounting arrangements as similar as possible to that of the intended service condition.
- Except for mechanical tests, all tests shall be carried out with the bushing mounted on a supporting structure with their ends in the media of the type in which they are intended to operate.

7.2 Test Conditions

7.2.1 Air temperature

The ambient temperature at the time of test shall be between 10 °C and 40 °C.

7.2.2 Humidity

The absolute humidity at the time of test shall be between 1,0 g/m^3 and 15,0 g/m^3.

7.2.3 Correction factors

Correction factors shall be in accordance with IEC 60137:2008, Table 7. In addition the following may be applied

- DC voltage withstand test: correction factors $k_1 \times k_2$.
- Polarity reversal test: no correction.

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For cases where the maximum specified valve hall ambient air temperature exceeds 40 °C, test voltages shall be corrected for the high ambient temperature and specified minimum ambient air humidity. Equivalent "reference ambient air" test voltages shall be calculated by dividing test voltages by calculated k_1 and/or k_2 where applicable. Reference ambient air is considered to be 20 °C, a relative humidity of 60 % (11g/m^3) and atmospheric air pressure of 101,3 kPa. Test voltages shall be further corrected for differences between atmospheric conditions within the test bay and reference ambient air conditions.

7.3 Test classification

7.3.1 Type (or design) tests

Type tests are those made to determine the adequacy of the design of a particular type, style, or model of power apparatus bushing; to meet its assigned ratings, to operate satisfactorily under usual service conditions or under special conditions if specified, and to demonstrate compliance with appropriate standards of the industry.

Type tests are made only on representative bushings to substantiate the ratings assigned to all bushings of the same design. These tests are not intended to be made as a part of normal production. The applicable portions of these tests may also be used to evaluate modifications of a previous design and to assure that performance has not been adversely affected. Test data from previous designs may be used for current designs where appropriate. Once made, the tests need not be repeated unless the design is changed so as to modify performance.

During the type tests, the bushing will be stressed higher than usually encountered in service and must withstand these tests without evidence of partial or complete failure. Hidden damage that may occur during type testing can usually be detected by comparing initial and final values of capacitance, dissipation factor and partial discharge quantity.

Type tests are included in Table 2; applicability to particular bushing types is detailed in the relevant clause.

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Table 2 – Type, routine and special tests

Test	Clause		
	Type	Routine	Special
Measurement of dissipation factor and capacitance		9.1	
Power-frequency voltage withstand	8.1	9.3	
Dry lightning impulse voltage withstand	8.2	9.2	
Dry or wet switching impulse voltage withstand	8.3	9.6	
DC applied voltage withstand with partial discharge measurement	9.4	9.4	
DC polarity reversal	9.5	9.5	
Electromagnetic compatibility (EMC)	8.4		
Temperature rise	8.5		
Cantilever load withstand	8.6		
Tightness test on liquid-filled, compound-filled and liquid-insulated bushings	8.7		
Internal pressure test on gas-filled, gas insulated and gas impregnated bushings	8.8		
Verification of dimensions	8.9	9.12	
Draw-lead bushing cap pressure	8.10		
Test of tap insulation		9.7	
Internal pressure test on gas-filled, gas-insulated and gas-impregnated bushings		9.8	
Tightness test on liquid-filled, compound-filled and liquid-insulated bushings		9.9	
Tightness test on gas-filled, gas-insulated and gas-impregnated bushings		9.10	
Tightness test at flange or other fixing device		9.11	
Artificial pollution withstand			10.1
Even wetting DC voltage withstand			10.2
Uneven wetting DC voltage withstand			10.3

7.3.2 Routine tests

Routine tests are included in Table 2; applicability to particular bushing types is detailed in the relevant clause. The sequence of tests is not specified and may be agreed between purchaser and supplier. It is recommended that tests of tap insulation and tightness tests are performed before dielectric test. Measurement of dissipation factor and capacitance shall be performed before and after withstand tests to verify no change in the condition of the bushing.

7.3.3 Special tests

Special tests are included in Table 2 and shall only be performed when contractually agreed upon between purchaser and supplier. These tests are applicable only to outdoor bushings.

8 Type tests

8.1 Dry power-frequency voltage withstand test with partial discharge measurement

8.1.1 Applicability

This test is applicable to all types of bushings.

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8.1.2 Test method and requirements

The testing shall be performed as specified in 9.3.2 except that the voltage U_{ac} in step c) shall be applied for 1 h. Partial discharge measurements shall be made continuously and a recording shall be taken at 5 min intervals.

8.1.3 Acceptance

The acceptance criteria in respect of partial discharge levels are in accordance with 9.3.3. If a flashover occurs outside the insulating envelope, the test may be repeated. If the repeat test also results in a flashover, the bushing shall be deemed to have failed.

Flashovers that are proven to be external to the test object shall be disregarded.

8.2 Dry lightning impulse voltage withstand test (BIL)

8.2.1 Applicability

This test is applicable to all types of bushings.

8.2.2 Test method and requirements

The full-wave test voltage shall be as specified by the purchaser.

The tests shall be performed with the following sequence of applications:

- 15 full lightning impulses of positive polarity, followed by
- 15 full lightning impulses of negative polarity

of the standard lightning impulse 1,2/50 μs.

Bushings for transformers of BIL greater than 550 kVp shall be subjected to

- 15 full lightning impulses of positive polarity, followed by
- 1 full lightning impulse of negative polarity at 110 % of the rated BIL, followed by
- 5 chopped lightning impulses of negative polarity at 121 % of the rated BIL, and by
- 14 full lightning impulses of negative polarity at 110 % of the rated BIL.

The time to sparkover on the chopping device shall be between 2 μs and 6 μs.

It is permissible, after changing polarity, to apply some impulses of minor amplitude before the application of the test impulses. The time intervals between consecutive applications of the voltage shall be sufficient to avoid effects from the previous applications of voltage.

8.2.3 Acceptance

The bushing shall be deemed to have passed the test if the criteria given in IEC 60137:2008 (8.3.3) are met.

8.3 Dry or wet switching impulse voltage withstand test (SIL)

8.3.1 Applicability

The dry test is applicable to all bushings. The wet test is applicable to outdoor bushings. When a wet test is made, a dry test is not necessary.

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8.3.2 Test method and requirements

To simulate the service condition, the bushing shall comply with the conditions as mentioned in 7.1. Artificial rainfall conditions shall comply with Table 1 of IEC 60060-1:2010 (Precipitation conditions for standard procedure).

NOTE Even distribution of rain over very long insulators is difficult and special agreement may be needed.

The test voltage value shall be as specified by the purchaser. The test procedure shall be in accordance with the requirements given in IEC 60137:2008 (8.4.2).

8.3.3 Acceptance

The bushing shall be deemed to have passed the test if the criteria given in IEC 60137:2008 (8.4.3) are met.

8.4 Electromagnetic compatibility tests (EMC)

8.4.1 Emission test

8.4.1.1 Applicability

This test is applicable for all types of bushings having a rated continuous DC voltage equal to and above 150 kV.

8.4.1.2 Test method and requirements

The test setup shall be prepared as described under the equivalent clause in IEC 60137. Calibration methods for the measuring instrument and for the measuring circuit are given in CISPR 16-1 and CISPR 18-2 respectively.

An AC voltage equal to 1,1 $U_p/\sqrt{2}$ shall be applied to the bushing and maintained for at least 5 min, U_p being the rated peak voltage (see clause 4.1.2). The voltage shall then be decreased by steps down to 0,3 $U_p/\sqrt{2}$, raised again by steps to the initial value and finally decreased by steps to 0,3 $U_p/\sqrt{2}$. At each step a radio interference measurement shall be taken and the radio interference level, as recorded during the last series of voltage reductions, shall be plotted versus the applied voltage; the curve so obtained is the radio interference characteristic of the bushing. The amplitude of voltage steps shall be approximately 0,1 $U_p/\sqrt{2}$.

8.4.1.3 Acceptance

The bushing shall be considered to have passed the test if the radio interference level at 1,1 $U_p/\sqrt{2}$ does not exceed 2 500 µV. Temporary discharge activities, which can rise up during major voltage adjustments, may be neglected.

If it can be shown that the bushing, without external shielding, is partial discharge free, i.e. there is no discharge above the background noise level specified in 9.3.2, it can be considered to pass the emission test requirements without the need for test.

8.4.2 Immunity test

DC bushings are not affected by possible electro-magnetic emissions. This test is therefore not required

8.5 Temperature rise test

8.5.1 Applicability

This test is applicable to all types of bushings.

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8.5.2 Test method and requirements

Testing shall be carried out in accordance with IEC 60137:2008 (8.7). Other test conditions may be used which reflect the particular service conditions (see 5).

The temperature of the surrounding air shall be between 10 °C and 40 °C. No corrections for variation of the ambient temperature within this range shall be applied. For projects where the HVDC valve hall air ambient temperature exceeds 40 °C the valve hall bushing air side should preferably be enclosed during the temperature rise test. The enclosure should be large enough not to interfere with thermal convection of air along the bushing surface, and simulate the maximum specified valve hall ambient air temperature with a tolerance of ± 2 °C. If the thermal test is performed without simulating the valve hall ambient air temperature, for example, performed at normal laboratory air temperature (between 10 °C and 40 °C), then the maximum allowable bushing hot-spot and air terminal temperatures shall be reduced by a pre-defined quantity. This quantity depends on the media to which the bushing is in contact during the test. It may be set to the difference between the maximum valve hall ambient air temperature and the ambient temperature during test. If it can be demonstrated by calculations basing on real tests that the influence of the hall air ambient temperature on the bushing hot-spot is lower than this simple difference, the reduction quantity may be lower.

The use of a typical service connector is recommended during the temperature rise test as the air side terminal working temperature could be the critical point at the high ambient air temperatures prevailing in the HVDC valve hall.

DC bushings (wall and transformer bushings) are subject to significant harmonic current content. Such harmonic current can not be easily reproduced in laboratories. Equivalent DC and AC power frequency current (50 Hz or 60 Hz) shall then be used. The amplitude of the equivalent test current shall produce the same total watt losses calculated for the specified harmonic current spectrum.

The equivalent test current shall be calculated as follows or by other agreed methods:

$$I_{\mathrm{eq,DC}} = \sqrt{\frac{I_{\mathrm{DC}}^2 x R_{\mathrm{DC}} + \sum_{h=1}^{n} I_h^2 x R_h}{R_{\mathrm{DC}}}} \quad (4)$$

In the case of power frequency test

$$I_{\mathrm{eq,AC}} = \sqrt{\frac{I_{\mathrm{DC}}^2 x R_{\mathrm{DC}} + \sum_{h=1}^{n} I_h^2 x R_h}{R_{\mathrm{AC}}}} \quad (5)$$

See the list of variables in 3.2.

The R_{h} values should be determined by measurements or calculations. The calculation method outlined in IEEE Std C37.23 may be used. Other calculation methods involving finite element models may be used if they have been proven to be adequate. The calculation method should be agreed upon.

NOTE Annex B gives further information on the determination of equivalent current.

8.5.3 Acceptance

The bushing shall be deemed to have passed the test if the limits of IEC 60137:2008 (Table 2) are met.

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8.6 Cantilever load withstand test

8.6.1 Applicability

The test is applicable to all types of bushings (air side).

8.6.2 Test method and requirements

The test values shall be in accordance with Table 3.

The test shall be carried out in accordance with the requirements given in IEC 60137:2008 (8.9.2).

For bushings having more than one terminal at the air end, the full test load shall be applied to each terminal successively. For wall bushings each side shall be tested separately.

Table 3 – Minimum values of cantilever withstand load

Rated lightning impulse withstand voltage kV	**Rated current A**					
	≤ 1 250		**> 1 250 to < 3 150**		**≥ 3 150**	
	Cantilever operating load N (Newton)					
	Normal load	**Heavy load**	**Normal load**	**Heavy load**	**Normal load**	**Heavy load**
< 450	625	1 000	1 000	1 575	2 000	2 000
450 to 650	800	1 575	1 250	2 000	2 000	2 000
750 to 950	800	2 000	1 250	2 500	2 000	2 500
≥ 1 050	1 250	2 000	1 575	2 500	2 500	2 500
	Cantilever test load N (Newton)					
	Normal load	**Heavy load**	**Normal load**	**Heavy load**	**Normal load**	**Heavy load**
< 450	1 250	2 000	2 000	3 150	4 000	4 000
450 to 650	1 600	3 150	2 500	4 000	4 000	4 000
750 to 950	1 600	4 000	2 500	5 000	4 000	5 000
≥ 1 050	2 500	4 000	3 150	5 000	5 000	5 000

NOTE 1 These values are modified from IEC 60137:2008, Table 1 for harmonization and regrouped.

NOTE 2 Cantilever operating loads include terminal load and wind pressure (70 Pa), see IEC 61463.

NOTE 3 For bushings operating at an angle >30° to the vertical, the effect of bushing self weight should be considered. The values given above correspond to vertical bushings that are to be tested in a vertical position. If a tilted or horizontal bushing is to be tested vertically, then an equivalent force shall be added to achieve the bending moment at the flange caused by the weight of the bushing in its operating position. If a vertical bushing is to be tested horizontally, then the test load can be reduced in the same manner. Equipment not attached during test, such as shielding arrangement, should be compensated for with corresponding mass attached in similar way as in operation

NOTE 4 For bushings, where upper and lower insulating envelopes are assembled by clamping force on the central fixing conductor, it is recommended to choose the cantilever test load taking into account the thermal expansion of the conductor due to the rated current flow.

NOTE 5 Other cantilever operating loads may be specified but the test load should always be at least twice the operating load.

NOTE 6 To convert from Newton to pound-force multiply the values of cantilever withstand load by 0,225.

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8.6.3 Acceptance

The bushing shall be deemed to have passed the test if the criteria given in IEC 60137:2008 (8.9.3) are met.

8.7 Tightness test on liquid-filled, compound-filled and liquid-insulated bushings

This test shall be carried out in accordance with IEC 60137:2008 (8.10).

8.8 Internal pressure test on gas-filled, gas-insulated and gas-impregnated bushings

This test shall be carried out in accordance with IEC 60137:2008 (8.11), IEC 61462 or IEC 62155, where appropriate.

8.9 Verification of dimensions

This test shall be carried out in accordance with IEC 60137:2008 (8.13).

8.10 Draw-lead bushing cap pressure test

8.10.1 Applicability

This test is applicable to all immersed bushings having a draw-lead conductor.

8.10.2 Test method and requirements

The bushing shall be assembled as for normal operation. A pressure of 1 bar gauge ± 0,1 bar shall be applied inside the bushing cap assembly and draw-lead central tube for a period if 1 h.

8.10.3 Acceptance

The bushing shall be considered to have passed the test if there is no evidence of leakage.

9 Routine tests

9.1 Measurement of dielectric dissipation factor (tan δ) and capacitances

9.1.1 Applicability

This test is applicable to all capacitance graded bushings.

9.1.2 Test method and requirements

Dielectric dissipation factor (tan δ) and capacitance measurements shall be made before and after the dry power-frequency voltage withstand test and the DC tests (7.3.2) and in accordance with IEC 60137:2008 (9.1).

These measurements shall be made at a voltage between 2 kV and 20 kV and at a voltage not exceeding the dry power-frequency withstand voltage. The tan δ and the capacitance measurement methods shall be in accordance with IEC 60137:2008 (9.1.2).

9.1.3 Acceptance

The bushing shall be deemed to have passed the test if the changes are within the limits stated in Table 4.

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Table 4 – Maximum values of tan δ and tan δ increase

Type of bushing insulation	Maximum Value of tan δ			Capacitance
	Value at highest test voltage	Increase between 10 kV and highest test voltage	Acceptable change [a]	Acceptable change %[b]
Oil-impregnated paper	0,005	0,000 2	+0,000 2	+1,0
Resin-impregnated paper	0,007	0,000 4	+0,000 4	+1,0
Gas	0,005	0,000 2	+0,000 2	+1,0

[a] The arithmetic difference in tan δ measured at 10 kV or at highest test voltage before and after withstand voltage tests shall be within the specified limits. For example, if the tan δ of oil-impregnated paper bushing was 0,40 % before the withstand tests, the maximum acceptable tan δ after the tests shall be 0,42 %

[b] The percentage change in capacitance after the withstand voltage tests based on the initial value shall be within the specified limit. The measurement shall be made at a voltage given in 9.1.2. The limit for capacitance-graded bushings is based on an arrangement of 100 capacitive layers. If the number of capacitive layers differs from 100 then the limit shall be (1/number of layers) × 100.

9.2 Dry lightning impulse voltage withstand test (BIL)

9.2.1 Applicability

This test is applicable to all DC bushings with dry lightning impulse voltage withstand of 550 kV or greater. Where the rated SIL exceeds 83 % of the BIL then, by agreement between purchaser and supplier, a routine dry lightning and/or dry switching impulse voltage withstand test may be carried out (see 9.6).

9.2.2 Test method and requirements

The test shall be carried out in accordance with IEC 60137:2008 (9.2.2).

The test voltage shall be as specified by the purchaser.

9.2.3 Acceptance

The bushing shall be deemed to have passed the test if there is no flashover or puncture of the insulation. To prove the absence of puncture during the test recording of the grounding current is advisable.

9.3 Dry power-frequency voltage withstand test with partial discharge measurement

9.3.1 Applicability

This test is applicable to all bushings.

9.3.2 Test method and requirements

The test shall be performed generally as specified in IEC 60137 and IEC 60270 and as specified below. The test shall be made at a frequency of 50 Hz or 60 Hz.

a) Measurement of partial discharges at a test voltage U_{ac} r.m.s., calculated as follows:

- For converter transformer bushings:

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$$U_{AC} = 1{,}15 \times \frac{1{,}5}{\sqrt{2}} \times \left[(N - 0{,}5) \times U_{dm} + \frac{\sqrt{2}}{\sqrt{3}} \times U_{vm} \right] \tag{6}$$

- For smoothing reactor bushings:

$$U_{AC} = 1{,}15 \times \frac{1{,}5}{\sqrt{2}} \times N \times U_{dm} \tag{7}$$

- For wall (roof) bushings, the test voltages shall be calculated as above, as applicable, except that the factor 1,15 shall be reduced to 1,0.
  - Converter transformer side:

$$U_{AC} = 1{,}0 \times \frac{1{,}5}{\sqrt{2}} \times \left[(N - 0{,}5) \times U_{dm} + \frac{\sqrt{2}}{\sqrt{3}} \times U_{vm} \right] \tag{8}$$

  - DC side:

$$U_{AC} = 1{,}0 \times \frac{1{,}5}{\sqrt{2}} \times N \times U_{dm} \tag{9}$$

b) A 1 min dry withstand test shall be carried out at AC r.m.s. voltage level equal to the dry lightning impulse withstand voltage level divided by 2,1. If BIL/2,1 is less than U_{ac} for the bushing, then proceed with U_{ac} for 60 s as the power frequency withstand test level. No partial discharge measurements are required during this test.

c) Repeat measurements of partial discharge at voltage equivalent to U_{ac} shall be made.

9.3.3 Acceptance

The bushing shall be considered to have passed the test if no flashover or puncture occurs and the partial discharge quantity does not exceed 10 pC as shown in Table 5. If there is a puncture, the bushing shall be considered to have failed the test. For capacitance graded bushings, it is assumed that a puncture has occurred if the capacitance measured after the test rises above the capacitance previously measured by about the amount attributable to the capacitance of one layer. If a flashover occurs the test shall be repeated once only. If, during the repetition of the test, no flashover or puncture occurs, the bushing shall be considered to have passed the test.

Table 5 – Maximum values of partial discharge quantity

Type of bushing insulation	Maximum discharge quantity pC measured at
	U_{ac}
Oil-impregnated paper	10
Resin-impregnated paper	10
Gas	10

9.4 DC applied voltage withstand test with partial discharge measurement

9.4.1 Applicability

This test is applicable to all DC bushings with a rated DC continuous voltage of 150 kV or higher. For DC bushings having rated voltage less than 150 kV, the DC routine tests shall be performed as sample tests. For such tests, one bushing out of 6 bushings belonging to the same manufacturing lot shall be DC tested. If the bushing failed one of the DC tests, two

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further bushings belonging to the same manufacturing lot shall be subjected to DC tests. If one of the additional two bushings fails one of the tests all bushings of the manufacturing lot shall be DC tested.

9.4.2 Test method and requirements

During the test, the temperature of the oil shall be between 10 °C and 40 °C.

For wall bushings, no preconditioning of the insulation structure at a lower voltage level is permitted and the DC voltage shall be raised to the test level within a period not exceeding 1 min. For bushings to be installed on converter transformers or on smoothing reactors, the DC voltage shall be raised to the converter transformer or the smoothing reactor DC voltage test level within a period not exceeding 1 min and then raised to the bushing DC voltage test level within the next minute. For all cases, the DC voltage shall then be held for 2 h, after which the voltage shall be reduced to zero within a period not exceeding 1 min.

Partial discharge measurements using measuring equipment as specified in IEC 60270 shall be performed during the entire DC applied voltage withstand test. Positive polarity shall be used.

The DC test voltage shall be calculated as follows:

- For converter transformer bushings:

$$U_{\mathrm{dc}} = 1{,}15 \times 1{,}5 \times \left[(N - 0{,}5) \times U_{\mathrm{dm}} + 0{,}7 \times U_{\mathrm{vm}} \right] \quad (10)$$

- For smoothing reactor bushings:

$$U_{\mathrm{dc}} = 1{,}15 \times 1{,}5 \times N \times U_{\mathrm{dm}} \quad (11)$$

- For wall bushings, the test voltage shall be as for the appropriate plant to which it is connected except that the multiplier 1,15 shall be reduced to 1,0.
  - Converter transformer side:

$$U_{\mathrm{dc}} = 1{,}0 \times 1{,}5 \times \left[(N - 0{,}5) \times U_{\mathrm{dm}} + 0{,}7 \times U_{\mathrm{vm}} \right] \quad (12)$$

  - DC side:

$$U_{\mathrm{dc}} = 1{,}0 \times 1{,}5 \times N \times U_{\mathrm{dm}} \quad (13)$$

9.4.3 Acceptance

The bushing shall be considered to have passed the test if:

- No more than 10 pulses of partial discharge with magnitude equal to or greater than 2 000 pC are recorded during the last 30 min of the test. Pulses that are proven to be external to the test object shall be disregarded. If this condition is not met, then the test may be extended for 30 min, with the aforementioned criteria applying. There may be only one 30 min extension.
- No flashover or puncture shall occur. If there is a puncture, the bushing shall be considered to have failed the test. For capacitance graded bushings, it is assumed that a puncture has occurred if the capacitance measured after the test rises above the capacitance previously measured by about the amount attributable to the capacitance of one layer. If a flashover occurs, the test shall be repeated once only. If, during the repetition of the test, no flashover or puncture occurs, the bushing shall be considered to have passed the test.

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NOTE The use of a partial discharge v time distribution curve may be useful in comparing the performance of bushings of a similar type.

9.5 Polarity reversal test with partial discharge measurement

9.5.1 Applicability

This test is applicable to all DC bushings with a rated DC continuous voltage of 150 kV or higher. For DC bushings having rated voltage less than 150 kV, the DC routine tests shall be performed as sample tests. For such tests, one bushing out of 6 bushings belonging to the same manufacturing lot shall be DC tested. If the bushing failed one of the DC tests, two further bushings belonging to the same manufacturing lot shall be subjected to DC tests. If one of the additional two bushings fails one of the tests all bushings of the manufacturing lot shall be DC tested.

9.5.2 Test method and requirements

During the test, the temperature of the oil, if applicable, shall be between 10 °C and 40 °C.

A double reversal test shall be used as shown in Figure 2.

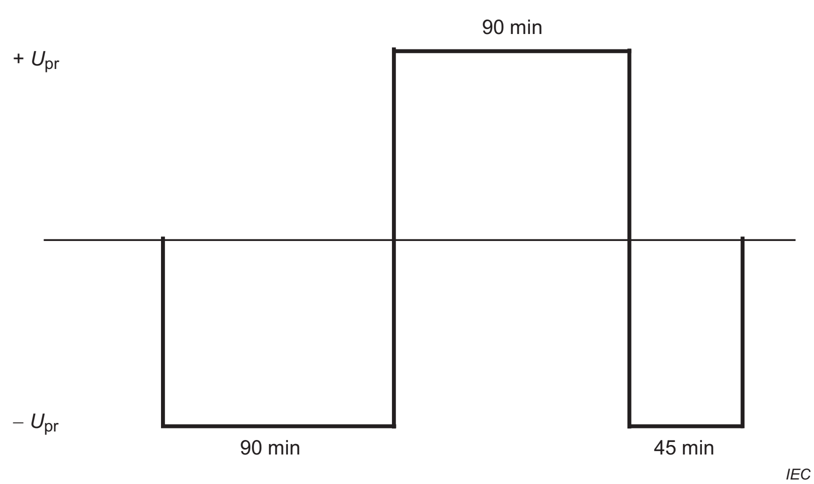

Figure 2 – Polarity reversal test profile

The polarity reversal test shall be performed after the DC applied voltage withstand test.

No preconditioning of the insulation structure at lower voltage is permitted. After the DC applied voltage withstand test, the bushing shall normally be earthed and completely discharged before the polarity reversal test is initiated. The time duration required for a complete discharge shall be agreed between the parties according to the type of bushing and shall be long enough to avoid any undue influence of the trapped charges on the results of this test.

However, in order to save time during routine tests and upon agreement between the parties, the polarity reversal test may be initiated at any time after the DC applied voltage withstand test.

The test sequence shall comprise:

- 90 min at negative polarity followed by
- 90 min at positive polarity followed by

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- 45 min at negative polarity and
- reduce the voltage to zero.

The time for the polarity reversal shall be as short as possible, consistent with the testing equipment available, but in no case more than 2 min. The polarity reversal shall be considered to be complete when the voltage has reached 100 % of the test value. The partial discharge levels shall be monitored during the entire test sequence.

Partial discharge measurements shall be made with equipment as specified in IEC 60270.

The polarity reversal test voltage shall be calculated as follows:

- For converter transformer bushings:

$$U_{\text{pr}} = 1{,}15 \times 1{,}25 \times \left[\left(N - 0{,}5 \right) \times U_{\text{dm}} + 0{,}35 \times U_{\text{vm}} \right] \qquad (14)$$

- For smoothing reactor bushings:

$$U_{\text{pr}} = 1{,}15 \times 1{,}25 \times N \times U_{\text{dm}} \qquad (15)$$

- For wall bushings, the test voltage shall be as for the appropriate plant to which it is connected except that the multiplier 1,15 shall be reduced to 1,0.
  - – Converter transformer side:

$$U_{\text{pr}} = 1{,}0 \times 1{,}25 \times \left[\left(N - 0{,}5 \right) \times U_{\text{dm}} + 0{,}35 \times U_{\text{vm}} \right] \qquad (16)$$

  - – DC side:

$$U_{\text{pr}} = 1{,}0 \times 1{,}25 \times N \times U_{\text{dm}} \qquad (17)$$

9.5.3 Acceptance

The bushing shall be considered to have passed the test if:

- No more than 10 pulses of partial discharge with magnitude equal to or greater than 2 000 pC are recorded during any sliding 30 min window of the test time excluding the reversal periods.
- No flashover or puncture shall occur. If there is a puncture, the bushing shall be considered to have failed the test. For capacitance graded bushings, it is assumed that a puncture has occurred if the capacitance measured after the test rises above the capacitance previously measured by about the amount attributable to the capacitance of one layer. If a flashover occurs the test shall be repeated once only. If, during the repetition of the test, no flashover or puncture occurs, the bushing shall be considered to have passed the test.

NOTE The use of a partial discharge v time distribution curve may be useful in comparing the performance of bushings of a similar type.

9.6 Dry Switching impulse withstand test

9.6.1 Applicability

This test is applicable to all DC bushings with dry lightning impulse voltage withstand of 550 kV or greater. where the rated SIL exceeds 83 % of the BIL. By contractual agreement a routine dry lightning and/or dry switching impulse voltage withstand test may be carried out.

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9.6.2 Test method and requirements

The test shall be carried out in accordance with 8.3 except that five negative polarity impulses only shall be applied.

The test voltage shall be as specified by the purchaser.

9.6.3 Acceptance

The bushing shall be deemed to have passed the test if there is no flashover or puncture of the insulation.

9.7 Test of tap insulation

This test shall be carried out in accordance with IEC 60137:2008 (9.5).

9.8 Internal pressure test on gas-filled, gas-insulated and gas-impregnated bushings

This test shall be carried out in accordance with IEC 60137:2008 (9.6) and IEC 61462 or IEC 62155, where appropriate.

9.9 Tightness test on liquid-filled, compound-filled and liquid-insulated bushings

This test shall be carried out in accordance with IEC 60137:2008 (9.7).

9.10 Tightness test on gas-filled, gas-insulated and gas-impregnated bushings

This test shall be carried out in accordance with IEC 60137:2008 (9.8).

9.11 Tightness test at the flange or other fixing device

This test shall be carried out in accordance with IEC 60137:2008 (9.9).

9.12 Visual inspection and dimensional check

This test shall be carried out in accordance with IEC 60137:2008 (9.10).

10 Special tests

On agreement between purchaser and manufacturer, special tests shall be performed only when the electrical strength of DC insulation of bushings under pollution (see 10.1) and even wetting surface conditions (see 10.2) determine the dimensions and the design of the insulation. In addition, it may be agreed to perform uneven wetting tests on wall bushings under conditions that reproduce certain peculiar positions in service as close as possible to reality (see 10.3).

NOTE 1 The electrical strength of a wall bushing may be affected by uneven wetting of the outdoor insulator surfaces which can take place when the mounting flange of bushing is shielded by the building wall, creating a dry zone.

NOTE 2 The uneven wetting of the insulator wall bushing surfaces may lead to flashover at much lower voltages than those obtained during pollution or wet test with uniformly wetted surfaces. In addition, the local current surging due to the uneven voltage distribution could overstress the internal insulation of the bushing, which may be detrimental for its integrity.

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10.1 Artificial pollution test

10.1.1 Applicability

An artificial pollution test may be applied to bushings having porcelain insulators to be used outdoors and exposed to polluted atmospheres.

10.1.2 Test method and requirements

If a test is deemed necessary, the specific test method to be applied and the degree of pollution withstand shall be specified or agreed upon between purchaser and manufacturer at the time of ordering. Proposals for artificial pollution test methods are described in IEC 61245.

NOTE The reproducibility of artificial pollution tests on bushings, with weather sheds of silicon rubber, performed in different laboratories has not been established in a manner consistent with other standardized tests. However, further guidance will become available as research continues and when appropriate inter-laboratory comparisons are made. The problem is under consideration by IEC TC 36: Insulators.

The DC withstand test voltage shall be specified. In general, it coincides with the rated continuous DC voltage. The tests are usually carried out at negative polarity.

10.1.3 Acceptance

The object of this test is to confirm withstand at the specified degree of pollution and specified test voltage. The specified characteristics of the bushing are confirmed if no flashover or puncture occurs during three consecutive individual tests performed in accordance with the specified or agreed procedure. If there is a puncture, the bushing shall be considered to have failed the test. If only one flashover occurs, a fourth test shall be performed and the bushing shall then be considered to have passed the test if no further flashover or puncture occurs.

10.2 Even wetting DC voltage test

10.2.1 Applicability

The even wetting test may be applied to all outdoor bushings.

10.2.2 Test method and requirements

The condition of the bushing and its mounting arrangement for the test shall be in accordance with the requirements prescribed in 7.1. Otherwise, the angle of mounting of the bushing for this test shall be the subject of a special agreement between purchaser and manufacturer.

The test circuit shall be in accordance with IEC 60060-1.

The standard even wetting test procedure described in IEC 60060-1 shall be used, except for the test duration.

If the actual atmospheric conditions deviate from the values given in IEC 60060-1, correction shall be made in accordance with IEC 60137:2008 (Table 7).

The test voltage to be applied to the bushing shall be equal to 1,25 times the rated continuous DC voltage at both positive and negative polarity.

The test voltage shall be maintained at this value for 1 h.

Rain with different characteristics representing very light or light conductive layers on the insulator surface or having different precipitation rates may be agreed between manufacturer and purchaser. The rain precipitation shall be adjusted before starting the test.

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10.2.3 Acceptance

The bushing shall be considered to have passed the test if no flashover or puncture occurs. If there is a puncture, the bushing shall be considered to have failed the test. If a flashover occurs, the test shall be repeated once only, after verifying the rain conditions.

The bushing shall be considered to have passed the test if no further flashover or puncture occurs.

10.3 Uneven wetting DC voltage test

10.3.1 Applicability

This test may be applicable to all outdoor bushings but it shall be agreed between purchaser and manufacturer.

10.3.2 Test method and requirements

The uneven wetting test is applicable to horizontal wall bushings for which the peculiar mounting arrangement in service may determine the reduction of the bushing's electrical strength. The condition of the bushing, the mounting arrangement representing service conditions and the dry zone width for the test shall be agreed between purchaser and manufacturer at the time of ordering.

NOTE The reproducibility of uneven wetting test made in different laboratories has not been established in a manner consistent with other standardized tests. However, further guidance will become available as research continues and when appropriate inter-laboratory comparisons are made.

As a guide, the following testing techniques may be adopted for the test. The dry zone located at groundside may be obtained by shielding the bushing from rain. It may be obtained by providing a rain-insulated shelter of suitable dimensions as close as possible to the bushing. The clearance between the shelter and the bushing shall be sufficient to avoid direct flashover to it. The rain water characteristics and precipitation rate shall be in accordance with the standard wetting test procedure described in IEC 60060-1. Rain with different characteristics, representing very light or light conductive layers on insulator surfaces, may be agreed between purchaser and manufacturer. The rain precipitation shall be adjusted before starting the test.

The test circuit shall be in accordance with IEC 60060-1.

The standard reference atmospheric conditions in accordance with IEC 60060-1 are not applicable and the actual atmospheric conditions shall be recorded.

The test voltage to be applied to the wall bushing shall be equal to 1,25 times the rated continuous DC voltage.

The wall bushing in its test position, and with the sheltered insulator surface still completely dry, is subjected to the specified test voltage and then the rain generation shall start. The test voltage shall be maintained until a total flashover occurs. Otherwise, it shall be maintained for at least 15 min from the start of the rain.

10.3.3 Acceptance

The bushing shall be considered as having passed the test if no flashover or puncture occurs. If there is a puncture, the bushing shall be considered to have failed the test. If a flashover occurs, the test shall be repeated once only, after verifying the rain conditions. The bushing shall be considered to have passed the test if no further flashover or puncture occurs.

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11 Recommendations for transport, storage, erection, operation and maintenance

It is essential that the transport, storage and installation of bushings, as well as their operation and maintenance in service, be performed in accordance with instructions given by the manufacturer.

Consequently, the manufacturer should provide instructions for the transport, storage, installation, operation and maintenance of bushings. The instructions for the transport and storage should be given at a convenient time before delivery, and the instructions for the installation, operation and maintenance should be given by the time of delivery at the latest.

It is impossible, here, to cover in detail the complete rules for the installation, operation and maintenance of each one of the different types of apparatus manufactured, but the following information is given relative to the most important points to be considered for the instructions provided by the manufacturer.

11.1 Conditions during transport, storage and installation

A special agreement should be made between manufacturer and user if the services conditions defined in the order, cannot be guaranteed during transport and storage. Special precautions may be essential for the protection of insulation during transport, storage and installation, and prior to energising, to prevent moisture absorption due, for instance, to rain, snow or condensation. Vibrations during transport should be considered. Appropriate instructions should be given.

Gas impregnated and gas-insulated bushings should be filled to a pressure sufficient to maintain positive pressure during transportation. A factory filling pressure of $1{,}3 \times 10^5$ Pa at 20 °C is appropriate for all temperature categories. If sulphur hexafluoride is used for filling the bushing during transportation it should comply with IEC 60376.

11.2 Installation

For each type of bushing the instructions provided by the manufacturer should at least include the items listed below.

11.3 Unpacking and lifting

Required Information for unpacking and lifting safely, including details of any special lifting and positioning devices necessary should be given.

At the arrival on site and before the final filling, the bushing should be checked according to the manufacturer instructions. For gas impregnated and gas insulated bushings, the gas pressure measured at ambient temperature should be above the atmospheric pressure.

11.4 Assembly

When the bushing is not fully assembled for transport, all transport units should be clearly marked. Drawings showing assembly of these parts should be provided with the bushing.

11.4.1 Mounting

Instructions for mounting of bushing shall be agreed between supplier and purchaser, these instructions should indicate:

- the total mass of the bushing;
- the mass of the bushing (or heaviest part if to be assembled on site) if exceeding 100 kg;
- the centre of gravity.

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The gas impregnated and gas insulated bushings should be filled with the specified gas, for example new sulphur hexafluoride complying with IEC 60376. The pressure of the gas at the end of filling, at the standard atmospheric air conditions (20 °C and 101,3 kPa), should be the rated filling pressure.

11.4.2 Connections

Instructions should include information on:

- connection of conductors, comprising the necessary advice to prevent overheating and unnecessary strain on the bushing and to provide adequate clearance distances;
- connection of any auxiliary circuits;
- connection of liquid or gas systems, if any, including size and arrangement of piping;
- connection for earthing.

11.4.3 Final installation inspection

Instructions should be provided for inspection and tests that should be made after the bushing has been installed and all connections have been completed.

These instructions should include:

- a schedule of recommended site tests to establish correct operation;
- procedures for carrying out any adjustment that may be necessary to obtain correct operation;
- recommendations for any relevant measurements that should be made and recorded to help with future maintenance decisions;
- instructions for final inspection and putting into service.

The results of the tests and inspection should be recorded in a commissioning report.

Gas impregnated and gas insulated bushings should be submitted to the following final checking:

– Measurement of gas pressure: the pressure of the gas measured at the end of filling and standard atmospheric air conditions (20 °C and 101,3 kPa) should be not less than the minimum functional pressure and not greater than the rated filling pressure of gas for insulation.

– Measurement of the dew point: the gas dew point at rated filling pressure should not exceed –5 °C when measured at 20 °C. Adequate corrections should be applied for measurement at the other temperatures.

– Enclosure tightness check: the check should be performed with the probing method for closed pressurised systems as specified for the routine test (see 9.8). The check should be started at least one hour after the filling of the bushing in order to reach a stabilised leakage flow. The check can be limited to gaskets, over pressure device, valves, terminals, manometers, temperature sensors, using a suitable leak detector.

11.5 Operation

The instructions given by the manufacturer should contain the following information:

- a general description of the equipment with particular attention to the technical description of its characteristics and all operation features provided, so that the user has an adequate understanding of the main principles involved;
- a description of the safety features of the equipment and their operation;
- as relevant, a description of the action to be taken to manipulate the equipment for maintenance and testing.

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11.6 Maintenance

11.6.1 General

The effectiveness of maintenance depends mainly on the way instructions are prepared by the manufacturer and implemented by the user

11.6.2 Recommendation for the manufacturer

The manufacturer should issue a maintenance manual including the following information:

1) schedule maintenance frequency;
2) detailed description of the maintenance work;
   - recommended place for the maintenance work (indoor, outdoor, in factory, on site, etc.);
   - procedures for inspection, diagnostic tests, examination, overhaul, function check out (e.g. limits of values and tolerances);
   - reference to drawings;
   - reference to part numbers (when applicable);
   - use of special equipment or tools (cleaning and degreasing agents);
   - precautions to be observed (e.g.; cleanliness).
3) comprehensive drawings of the details of the bushing important for maintenance, with clear identification (part number and description) of assemblies, sub-assemblies and significant parts;

   NOTE Exploded view drawings which indicate the relative position of components in assemblies and subassemblies are a recommended illustration method.
4) list of recommended spare-parts (description, reference number quantities) and advice for storage;
5) estimate of active scheduled maintenance time;
6) how to proceed with the equipment at the end of its operating life, taking into consideration environmental requirements.

The manufacturer should inform the users of a particular type of bushing about corrective actions required by possible systematic defects and failures.

Availability of spares: The manufacturer should be responsible for ensuring the continued availability of recommended spare parts required for maintenance for a period not less than 10 years from the date of the final manufacture of the bushing.

11.6.3 Recommendations for the user

a) If the user wishes to carry out his own maintenance, he should ensure that his staff has sufficient qualifications as well as a detailed knowledge of the bushing.
b) The user should record the following information:
   - the serial number and the type of the bushing;
   - the date when the bushing is put in service;
   - the results of all measurements and tests including diagnostic tests carried out during the life of the bushing;
   - dates and extent of the maintenance work carried out;
   - the history of service, records of the bushing measurements during and following a special operating condition (e.g. fault and post fault operating state);
   - references to any failure report.
c) In case of failure and defects, the user should make a failure report and should inform the manufacturer by stating the special circumstances and measures taken. Depending upon

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the nature of the failure, an analysis of the failure should be made in collaboration with the manufacturer.

d) In case of disassembling for reinstallation in the future, the user must record the time and storage conditions.

11.6.4 Failure report

The purpose of the failure report is to standardise the recording of bushing failures with the following objectives:

- to describe the failure using a common terminology;
- to provide data for the user statistics;
- to provide a meaningful feedback to the manufacturer;

The following gives guidance on how to make a failure report.

A failure report should include the following whenever such data is available:

a) Identification of the bushing, which failed:
   - substation name;
   - identification of the bushing (manufacturer, type, serial number, ratings);
   - bushing family (oil, resin or SF6 insulation,);
   - location (indoor, outdoor).
b) History of the bushing:
   - history of the storage;
   - date of commissioning of the equipment
   - date of failure/defect;
   - date of last maintenance;
   - date of the last visual checking of the oil level indicator
   - details of any changes made to the equipment since manufacture;
   - condition of the bushing when the failure/defect was discovered (in service, maintenance, etc.).
c) Identification of the sub-assembly/component responsible for the primary failure/defect:
   - high-voltage stressed components;
   - tapping;
   - other components.
d) Stresses presumed contributing to the failure/defect
   - environmental conditions (temperature, wind, snow, ice, pollution, lightning, etc.);
   - grid conditions (switching operations, failure of other equipment, etc.);
   - others.
e) Classification of the failure/defect
   - major failure;
   - minor failure;
   - defect.
f) Origin and cause of the failure/defect
   - origin (mechanical, electrical, tightness etc.);
   - cause in the opinion of the person having established the report (design, manufacture, inadequate instructions, incorrect mounting, incorrect maintenance, stresses beyond those specified, etc.).

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g) Consequences of the failures or defect
   - equipment down-time;
   - time consumption for repair;
   - labour cost;
   - spare parts cost.

A failure report may include the following information:

- drawings, sketches;
- photographs of defective components;
- single-line station diagram;
- records or plots;
- references to maintenance manual.

12 Safety

High-voltage equipment can be safe only when installed in accordance with the relevant installations rules, and used and maintained in accordance with the manufacturer’s instructions.

High-voltage equipment is normally only accessible by instructed persons. It should be operated and maintained by skilled persons. When unrestricted access is available to bushings, additional safety features may be required.

The following specifications in subclauses 12.1 to 12.3 provide personal safety measures for equipment against various hazards:

12.1 Electrical aspects

- insulation of the isolating distance
- earthing (indirect contact)
- IP coding (direct contact)

12.2 Mechanical aspects

- pressurised components
- mechanical impact protection

12.3 Thermal aspects

- flammability

13 Environmental aspects

The need to minimise the impact of the natural environment of bushings during all phases of their life is now recognised.

IEC Guide 109 gives guidance in this respect in term of life cycle impacts and recycling and disposal at the end of life.

The manufacturer should specify information regarding the relation between operation during service life, dismantling of the equipment and environmental aspects.

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Annex A
(informative)

A.1 Bushings used in voltage source converters (VSC) HVDC schemes

A.1.1 Introduction

This standard applies primarily to HVDC bushings of condenser type utilized with line commutated HVDC converters (LCC).

Recently new HVDC converter schemes using voltage source converter (VSC) technologies have been put in operation. The principle of operation of such converter technology is quite different than the usual technologies using line commutated converters. However, for DC bushings, this standard is applicable also for VSC HVDC schemes, even if the ratings may be different. The important thing is to be aware that new applications may result in special service conditions requiring additional information in the specification by the purchaser.

Different technologies regarding topologies and switching strategies may be used for voltage source DC converters. In a two- or three-level topology the valves act like controllable switches connecting the stiff DC voltage to the ac side, see Figure A.1. An alternative technology is that the valves are divided in modules, each module with its own DC capacitor. In this case each module acts like a two-level controllable voltage source, see Figure A.2. This is defined as a multi-level VSC.

It must be noted that any of the technologies, two-level or multi-level VSC, may be used in any of the configurations. Thus, these figures show only typical examples of VSC schemes. Other schemes are also feasible. Furthermore, depending on the specific conditions for each scheme, some of the equipment shown in the figures may be omitted.

The technical requirements for bushings for VSC HVDC may differ from those for classic HVDC with line commutated converters. However, the same parameters have to be specified.

Even if the requirements differ from traditional LCC HVDC schemes, this standard also applies to the DC bushings in VSC schemes when the specification is adapted to the operation conditions and stresses applicable for the scheme.

Figure A.1 below shows a simplified VSC HVDC application circuit for two-level converter topology with the locations for the bushings.

The converter bushings in Figure A.1 are continually exposed to transient voltage stresses in the form of repetitive large voltage steps. Furthermore, the harmonic currents are significant. In these aspects the operation conditions for the converter bushings in a two- and three-level VSC scheme differ significantly from the operation condition for bushings in an LCC HVDC scheme. These specific stresses for this application must be considered and specified by the purchaser.

The DC bushings in Figure A.1 are mainly exposed to direct voltage and direct current, with a small amount of voltage and current harmonics, in a similar way as for LCC.

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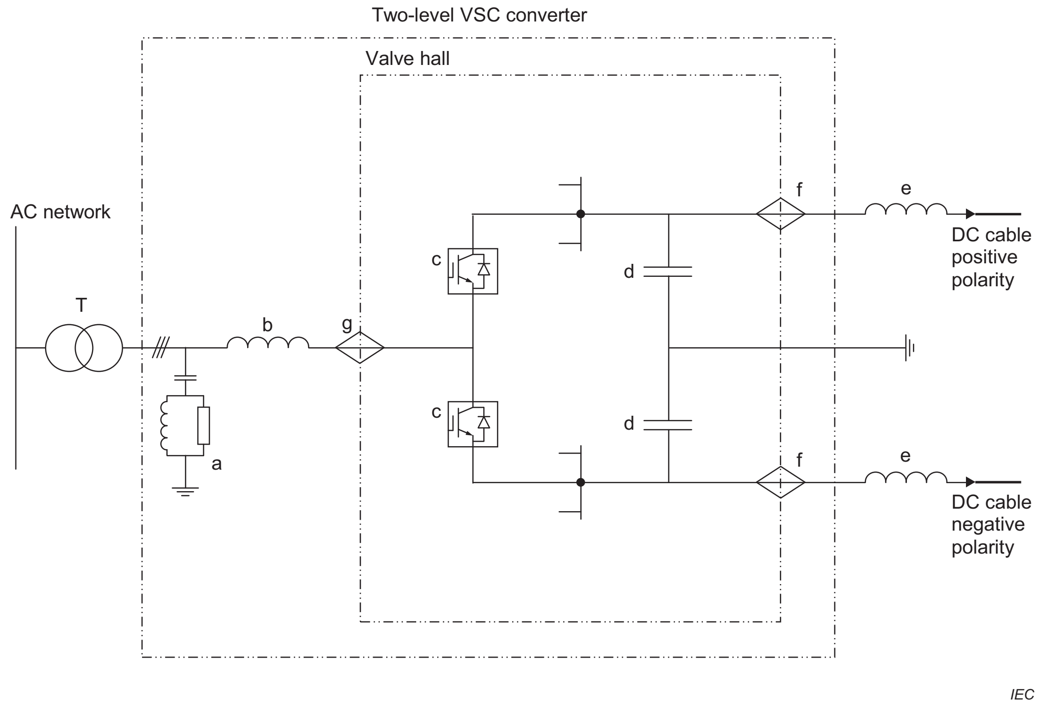

Key

a) AC filter

b) Converter reactor

c) Converter valve

d) DC capacitor

e) Smoothing reactor

f) DC bushings

g) Converter bushings

T) Transformer

Figure A.1 – Two-level VSC HVDC converter station applied in a bipolar scheme with DC cable transmission

Figure A.2 below shows a simplified VSC HVDC application circuit for multi-level converter topology with the locations for the bushings.

For the multi-level application the converter bushings are mainly exposed to DC and fundamental frequency currents. If required any additional harmonic contribution is to be considered and specified by the purchaser. As Figure A.2 shows the application in a monopolar HVDC scheme, the converter bushings are exposed to DC voltages to ground, as is the case for traditional HVDC bushings. In general the voltage stress of the bushings is to be specified depending on their location and configuration of the HVDC link.

The upper DC bushing in Figure A.2 (connected to the DC OH line) is mainly exposed to direct voltage and direct current, with a small amount of voltage and current harmonics, in a similar way as for LCC.

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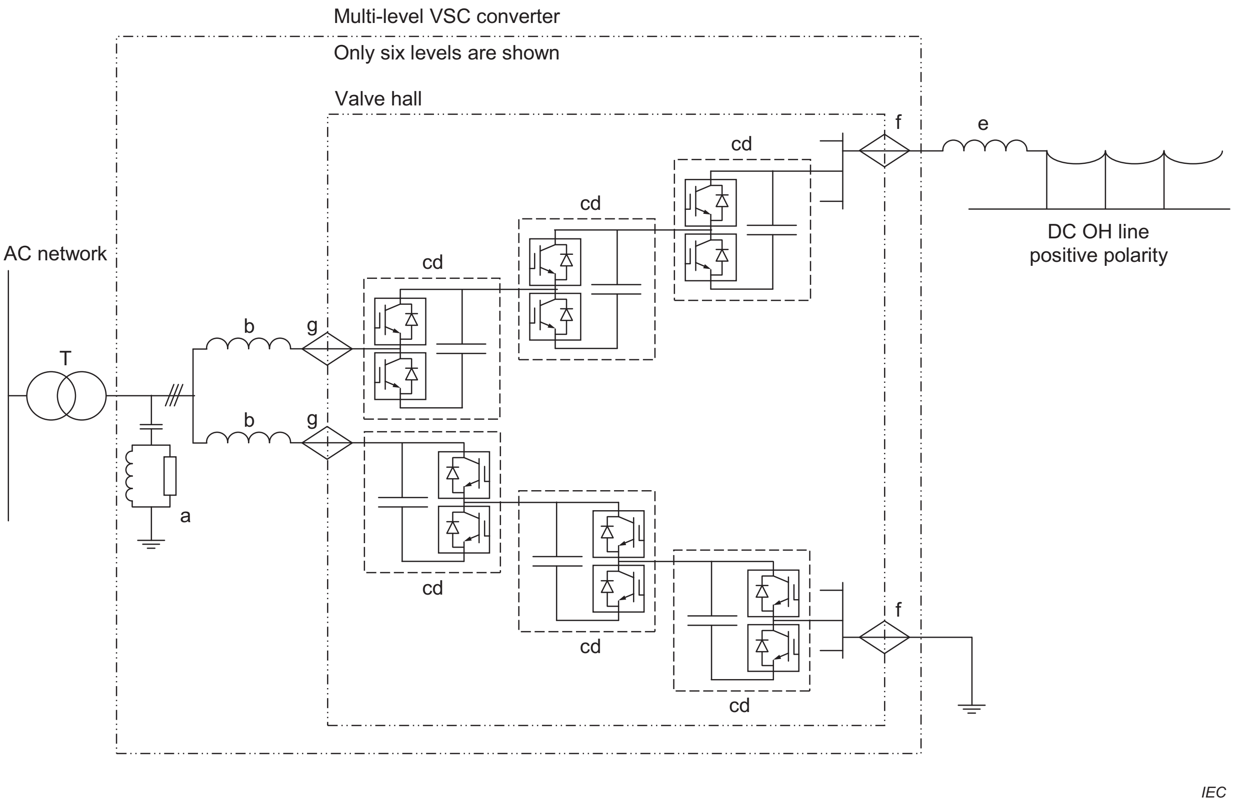

Key

a) AC filter (if applicable)

b) Converter reactor

cd) Power modules including DC capacitance

e) Smoothing reactor

f) DC bushings

g) Converter bushings

T) Transformer

NOTE The figure is simplified. A 20-level VSC converter requires 20 power modules.

Figure A.2 – Multi-level VSC HVDC converter station applied in a monopolar scheme with DC overhead line transmission

A.1.2 Design

In VSC converter applications there are no commutation failures leading to the discharge of the complete DC side capacitance. On the other hand, in some VSC topologies there is no possibility to reduce the DC side fault current by control actions in case of DC side short circuit. In such topologies short circuit current will be fed in from the AC network via diodes of the valves, until cleared by the AC side breakers, see Figures A.1 and A.2. In topologies that can interrupt DC side fault current the converter or DC breaker interrupts the fault current. Furthermore, discharge currents from large DC side capacitors have to be considered, when applicable, depending on circuit configuration. Consequently, maximum fault currents shall be specified in accordance with 4.3.2.2 and 4.3.2.3 of this standard.

As for line commutated applications, the harmonic currents through bushings used in VSC applications are low compared to the DC currents, but often in a higher frequency range.

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Especially for the converter bushings in Figure A.1, the current harmonics are more significant. The current harmonic spectrum shall be specified by the purchaser.

The transient voltage stresses and the voltage harmonic stresses should be considered in the design of the bushings. This is especially important for converter bushings used in a two- or three-level topology, see Figure A.1, but it should also be considered for other bushings. The purchaser should specify the voltage waveform for the switching transients and the voltage harmonic spectrum. Both the dielectric and thermal stresses should be considered. Bushings with low capacitance and dielectric dissipation factor at the frequency of the voltage transients are preferred in order to limit the heating that is caused by the voltage harmonics.

A.1.3 Tests

VSC HVDC transmission schemes are operated at fixed polarity, independent of the DC power direction. Therefore the polarity reversal test is not applicable to bushings used in VSC HVDC schemes where the polarity is fixed.

Besides the polarity reversal test, the test program should be similar as for line commutated HVDC applications

A.1.4 Supporting Published Material

Asplund, G., Erikson, K., Svenson, K. *DC transmission based on voltage source converters*, CIGRE SC 14 Colloquium, South Africa 1997.

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Annex B
(informative)

B.1 Temperature rise test methods for the determination of the equivalent test current

B.1.1 Introduction

Bushings for HVDC may be subject to significant harmonics currents. In particular the bushings connected to the transformer valve windings are subject to the same harmonics current that flow inside the transformer. DC wall bushings are less influenced by the harmonics because the current flowing to the DC yard has normally a low harmonic content.

To correctly evaluate the thermal effect of the distorted current during the design stage and to calculate the equivalent current for the temperature rise test it is necessary that the purchaser will specify the maximum current harmonic spectrum.

The numerator of Formulas (4) and (5) in 8.5.2, summarized in Formula (B.1), is composed by two terms, the first represents the losses due to the DC component in the current (if any) and the second the AC losses in distorted operation:

$$I_{DC}^2 \times R_{DC} + \sum_{h=1}^{h} I_h^2 \times R_h \qquad \text{(B.1)}$$

where

$I_{DC}^2 \times R_{DC}$ are the losses caused by the DC component in the bushing current; and

$\sum_{h=1}^{h} I_h^2 \times R_h$ are the losses caused by the AC and harmonic components in the bushing current (i.e. AC losses in distorted operation).

Concerning the way to calculate the AC losses in distorted operation, generally intended as sinusoidal plus the effect of the harmonics, there are different applicable methodologies:

- Analytical calculation.
- Finite element method calculation.
- Calculation by enhancement factors as described in IEC 61378-1.

This Annex B will describe the above points and will provide some calculation examples.

B.2 Basics concerning the losses in distorted operation

It is well known that in a conductor subject to an alternating current, losses are higher with respect to those generated by a DC current with the same r.m.s. value. This is caused by interaction between the current and the magnetic field that changes the current distribution inside the conductor moving the current toward the surface of the conductor (skin effect).

The total losses are normally calculated as two components, the first based on the DC resistance and the r.m.s. value of the current, the second calculated as an additional component named Eddy or additional losses that take into account of the increasing by the skin effect.

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The theoretical study of the Eddy losses is quite complex, the basic of the theory is described in IEC 61378-1 and IEC 61378-3.

B.3 Analytical calculation

The calculation of the ratio between AC and DC resistance can be done at each harmonic frequency based on the Dwight's curves reported in IEEE Std C37.23.

A simpler formula, based on a simplified version of the traditional hyperbolic functions, has been described by H. B. Dwight in his paper *Skin effect in tubular and flat conductors*, A.I.E.E., 1918.

Here is a version of the original formula, modified to take into account of metric units:

$$\frac{R_{AC}}{R_{DC}} = \frac{m \times t(r_{in} + r_{out})}{20 r_{out}\sqrt{2}}\left(1 + \frac{10}{m \times r_{out}\sqrt{2}} + \frac{300}{8m^2 r_{out}^2}\right) \quad \text{(B 2)}$$

where

f is the frequency (Hz);

ρ is the conductor resistivity (Ω m);

r_{in} is the inner radius of the conductor tube (mm);

r_{out} is the outer radius of the tube (mm);

t is the conductor tube wall thickness (mm); and

m is calculated as:

$$m = \sqrt{\frac{8\pi^2 f}{10^{11}\rho}} \quad \text{(B.3)}$$

Formula (B.2) gives the same results of the curves reported in IEEE Std C37.23 for $m \times t > 40$.

Formula (B.2) is applicable also to solid cylindrical rods.

The method described above can be used for the evaluation of the AC resistance at fundamental frequency and for each harmonic.

B.4 Finite element method calculation

Thanks to the progress of computers and mathematical theory of this method, the finite element method is now one of the most popular and reliable engineering verification tools.

Concerning the evaluation of the conductor losses, a 2D axial symmetric solver is adequate. 3D software could be applicable to very sophisticated analysis of some details like conductors with different profiles or particular coupling joints etc.

Due to the fact that normally the bushings do not have massive structures made by magnetic material software packages for non-linear problems are not necessary.

On the other hand the software has to be able to solve the magnetic problem under excitation sources, typically sinusoidal, and also take into account skin effect. This solution is named time harmonic.

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The software should have meshing software able to set very accurate meshes with manual and automatic functions for the mesh adaption.

To achieve reliable results it is fundamental to follow some simple rules in the modelling:

- Try to identify conditions of symmetry, both geometrical and magnetic, that allow simplification of the model. As a consequence the overall geometry can be 'sliced' in a smaller model that will be less 'heavy' for the numerical calculation.
- Enclose the model in a suitable space that defines the borderline of the field. On the external face of this container a condition Zero magnetic field will be applied. The proper size of this container can be assessed by setting several tentative solutions as a compromise of the accuracy of the results, the meshing capabilities and the overall calculation time.
- The mesh must be accurately refined in the metallic parts that are subject to the investigation, in particular the zone affected by the skin effect. As a practical rule, it is necessary that the area of the part most subject to the skin effect, i.e. practically equal to the skin depth for the given material at the given frequency, must be modelled with a triangular mesh that gives a minimum of 4 to 5 mesh elements in this zone.

In order to ensure a good accuracy in the areas involved by the skin effect during the runs at different frequencies, it is fundamental to check that the mesh solution at the various harmonics still remains well refined in the areas subject to the skin effect, in case it is necessary to improve it.

At this point it is possible to proceed with two different methodologies:

- Run the model at different harmonic frequencies but at equal current for each harmonic. The output for each run will be the losses at the given harmonic frequency and constant current. By making the ratio of each of these harmonic loss and the DC losses, calculated on the basis of the same r.m.s. value of the total injected current, it is possible to calculate the ratio $R_{\mathrm{AC,h}} / R_{\mathrm{DC}}$ for each harmonic, to be used in Formulas (4) and (5) in 8.5.2.
- Run the model at different harmonic currents and frequencies and get the losses for each harmonic. The total sum of these losses gives directly the AC losses in distorted operation to be used in Formulas (4) and (5) in 8.5.2.

B.5 Calculation by enhancement factors as described in IEC 61378–1

IEC 61378-1 follows a different concept based on the calculation of the losses in distorted operation based on the use of harmonics enhancement factors.

This calculation methodology is very simple, is normally applied to the convertor transformers and is particularly indicated for the transformer bushings.

In this paragraph the IEC 61378-1 designation rules will be followed.

The starting point is the calculation of the AC losses of the conductor at fundamental frequency and harmonic current (PC1) and of the corresponding DC losses calculated at fundamental harmonic current $(R_{\mathrm{C}} \times I_1^{2})$.

The calculation of P_{C1} can be done either by finite element method or by the analytical method, while the DC losses are calculated on the basis of the DC resistance (R_{C}) and the r.m.s. value of the fundamental harmonic current (I_1).

The Eddy losses at fundamental frequency (P_{CE1}) are calculated by difference between the two values:

$$P_{\mathrm{CE1}} = P_{\mathrm{C1}} - (R_{\mathrm{C}} \times I_1^2) \quad \text{(B.4)}$$

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To the Eddy losses component a harmonic enhancement factor will be applied that is calculated as:

$$F_{\mathrm{CE}} = \sum_{h=1}^{n} \left(\frac{I_h}{I_1}\right)^2 \times h^{0,8} \tag{B.5}$$

As a consequence, the total losses in distorted operation (P_N) are:

$$P_N = (I_{LN}^2 \times R_{\mathrm{C}}) + (F_{\mathrm{CE}} \times P_{\mathrm{CE1}}) \tag{B.6}$$

Where the term I_{LN} is the r.m.s. value of the current including the harmonics.

The above calculated parameter P_N can be used directly in Formulas (4) and (5) in 8.5.2 as AC losses in distorted operation component.

B.6 Examples of calculation

The starting point for the evaluation of the losses under distorted operation is the harmonic spectrum of the current that flows into the bushing. Table B.1 shows an example of the harmonic spectrum of the current of a valve side connected bushing.

Table B.1 – Valve side connected bushing current harmonic spectrum

Harmonic current spectrum	
Harmonic (*h*)	***I*h %**
DC	0,00
1	**100,00**
5	17,44
7	10,77
11	4,18
13	2,37
17	0,60
19	0,69
23	0,92
25	0,86
29	0,51
31	0,32
35	0,17
37	0,25
41	0,32
43	0,29
47	0,16

The harmonics listed in the above spectrum are referred to the fundamental harmonic. This spectrum has a Total harmonic distortion (THD %) equal to 21,2 % and the total distorted current equivalent r.m.s. value is 102,21 % of the first harmonic.

The following examples of calculations are referred to a copper rod with the following characteristics:

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ρ_{Cu} Conductor resistivity at 75 °C = 1,99 × 10^{-8} Ωm;

Rod diameter = 70 mm;

l Conductor length = 1 m;

I_1 First harmonic current (r.m.s.) = 2000 A;

I_h Table B.1 spectrum (%);

F Network frequency (equal to fundamental frequency) = 50 Hz

NOTE For convenience all calculations have been done on a conductor of 1 m length.

Based on the above data the conductor has a DC resistance (R_{dc}) at 75 °C of 5,171 97 μΩ.

This value will be the same for all the three different calculation methodologies.

B.6.1 Calculation based on the analytical method

Table B.2 shows the complete calculation of R_h and of the total losses due to the various harmonics.

The calculation is valid as $m \times t$ is > 40 for each harmonic.

Table B.2 – Calculation based on the analytical method

			R_h calculation based on Dwight's formula				
Harmonic (h)	f_h [Hz]	I_h [A]	M	$m \times t$	R_h/R_{DC}	R_h [Ω]	$R_h \times I_h^2$ [W]
1	**50**	**2 000,0**	1,0	49,3	2,020	**1,045 × 10^{-5}**	41,78
5	250	348,74	3,1	110,2	4,159	2,151 × 10^{-5}	2,62
7	350	215,44	3,7	130,4	4,871	2,519 × 10^{-5}	1,17
11	550	83,52	4,7	163,5	6,038	3,123 × 10^{-5}	0,22
13	650	47,31	5,1	177,7	6,541	3,383 × 10^{-5}	0,08
17	850	11,93	5,8	203,2	7,442	3,849 × 10^{-5}	0,01
19	950	13,85	6,1	214,9	7,853	4,061 × 10^{-5}	0,01
23	1150	18,38	6,8	236,4	8,613	4,455 × 10^{-5}	0,02
25	1250	17,14	7,0	246,5	8,969	4,639 × 10^{-5}	0,01
29	1450	10,29	7,6	265,4	9,640	4,986 × 10^{-5}	0,01
31	1550	6,45	7,8	274,4	9,958	5,150 × 10^{-5}	0,00
35	1750	3,43	8,3	291,6	10,560	5,464 × 10^{-5}	0,00
37	1850	4,94	8,6	299,8	10,860	5,614 × 10^{-5}	0,00
41	2050	6,31	9,0	315,6	11,410	5,903 × 10^{-5}	0,00
43	2150	5,76	9,2	323,2	11,680	6,042 × 10^{-5}	0,00
47	2350	3,29	9,7	337,9	12,200	6,311 × 10^{-5}	0,00
	I_L (r.m.s) [A]	**2044,10**				$\sum_{h=1}^{n} I_h^2 \times R_h =$	**45,92**

Then the calculations of the equivalent test currents are:

$$I_{eq,DC} = \sqrt{\frac{I_{DC}^2 \times R_{DC} + \sum_{h=1}^{n} I_h^2 \times R_h}{R_{DC}}} = \sqrt{\frac{0 + 45{,}92}{5{,}17197 \times 10^{-6}}} = 2979{,}7 \quad [A]$$

This is according to Formula (4) in 8.5.2. Instead, concerning Formula (5):

$$I_{eq,DC} = \sqrt{\frac{I_{DC}^2 \times R_{DC} + \sum_{h=1}^{n} I_h^2 \times R_h}{R_{AC}}} = \sqrt{\frac{0 + 45{,}92}{10{,}450 \times 10^{-6}}} = 2096{,}2 \quad [A]$$

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B.6.2 Calculation based on Finite Element Method

Table B.3 shows the value of each harmonic loss as it is calculated by the software:

Table B.3 – Calculation based on Finite Element Method

Harmonic (h)	f_h [Hz]	I_h [A]	Losses P_h [W]
1	**50**	**2 000,00**	**41,735**
5	250	348,74	2,616
7	350	215,44	1,168
11	550	83,52	0,218
13	650	47,31	0,075
17	850	11,93	0,008 48
19	950	13,85	0,007 79
23	1 150	18,38	0,015 0
25	1 250	17,14	0,013 6
29	1 450	10,29	0,005 3
31	1 550	6,45	0,002 14
35	1 750	3,43	0,000 64
37	1 850	4,94	0,001 37
41	2 050	6,31	0,002 35
43	2 150	5,76	0,002
47	2 350	3,29	0,000 68
	I_L (r.m.s) [A]	**2044,10**	$\sum_{h=1}^{n} I_h^2 \times R_h =$ **45,7**

To apply the formulas of 8.5.2 it is necessary to evaluate the AC resistance at fundamental harmonics (R_{ac}). This can be done on the basis of the losses at fundamental harmonic P_1.

$$R_{AC} = \frac{P_1}{I_1^2} = \frac{41{,}735}{2000^2} = 10{,}43375 \qquad [\mu\Omega]$$

Then the calculations of the equivalent test currents are:

$$I_{eq,DC} = \sqrt{\frac{I_{DC}^2 \times R_{DC} + \sum_{h=1}^{n} I_h^2 \times R_h}{R_{DC}}} = \sqrt{\frac{0 + 45{,}87}{5{,}17197 \times 10^{-6}}} = 2\,978 \qquad [A]$$

This is according to Formula (4) in 8.5.2. Instead, concerning Formula (5):

$$I_{eq,AC} = \sqrt{\frac{I_{DC}^2 \times R_{DC} + \sum_{h=1}^{n} I_h^2 \times R_h}{R_{AC}}} = \sqrt{\frac{0 + 45{,}87}{10{,}433\,75 \times 10^{-6}}} = 2096{,}7 \qquad [A]$$

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B.6.3 Calculation based on the enhancement factor according IEC 61378–1

Table B.4 shows the calculation of the enhancement factor F_{CE}:

Table B.4 – Calculation based IEC 61378-1 enhancement factor F_{CE}

Harmonic (h)	f_h [Hz]	I_h [A]		$(I_h/I_1)^2 \times h^{0,8}$
1	50	2 000,00		1
5	250	348,74		0,110
7	350	215,44		0,055
11	550	83,52		0,012
13	650	47,31		0,004
17	850	11,93		0,000
19	950	13,85		0,001
23	1 150	18,38		0,001
25	1 250	17,14		0,001
29	1 450	10,29		0,000
31	1 550	6,45		0,000
35	1 750	3,43		0,000
37	1 850	4,94		0,000
41	2 050	6,31		0,000
43	2 150	5,76		0,000
47	2 350	3,29		0,000
	I_L (r.m.s) [A]	2044,10	F_{CE}=	1,185

In this example the eddy losses and at fundamental frequency are calculated on the basis of the Finite Element Method:

$$P_{CE1} = P_{C1} - R_C \times I_1^2 = 41{,}735 - 5{,}171\,97 \times 10^{-6} \times 2000^2 = 21{,}0471 \qquad [W]$$

Then it is possible to calculate the AC losses in distorted operation:

$$P_N = \sum_{h=1}^{n} I_h^2 \times R_h = I_{LN}^2 \times R_C + F_{CE} \times P_{CE1} = 2044{,}1^2 \times 5{,}17197 \times 10^{-6} + 1{,}185 \times 21{,}0471 = 46{,}551 \qquad [W]$$

Finally the calculations of the equivalent test currents are:

$$I_{eq,DC} = \sqrt{\frac{I_{DC}^2 \times R_{DC} + \sum_{h=1}^{n} I_h^2 \times R_h}{R_{DC}}} = \sqrt{\frac{0 + 46{,}551}{5{,}171\,97 \times 10^{-6}}} = 3000{,}1 \qquad [A]$$

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This is according to Formula (4) in 8.5.2. Instead, concerning Formula (5):

$$I_{\text{eq,AC}} = \sqrt{\frac{I_{\text{DC}}^2 \times R_{\text{DC}} + \sum_{h=1}^{n} I_h^2 \times R_h}{R_{\text{AC}}}} = \sqrt{\frac{0 + 46{,}551}{10{,}43375 \times 10^{-6}}} = 2112{,}2 \qquad [\text{A}]$$

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ELECTROTECHNICAL
COMMISSION

3, rue de Varembé
PO Box 131
CH-1211 Geneva 20
Switzerland

Tel: + 41 22 919 02 11
Fax: + 41 22 919 03 00
info@iec.ch
www.iec.ch

IEEE Standards Association

445 Hoes Lane
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USA
http://standards.ieee.org/

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