



IEEE Standard General Requirements and Test Code for Dry-Type and Oil-Immersed Smoothing Reactors and for Dry-Type Converter Reactors for DC Power Transmission

IEEE Power and Energy Society

Developed by the
Transformers Committee

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(Revision of
IEEE Std 1277-2010)

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Abstract: The electrical, mechanical, and physical requirements of oil-immersed and dry-type air-core smoothing reactors and dry-type air-core converter reactors for high-voltage direct current (HVDC) applications are specified. Test code is defined and appropriate technical background information is presented or identified.

Keywords: construction, converter reactors, dry-type air-core, HVDC, IEEE 1277™, oil-immersed, rating, smoothing reactors, test code application

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Introduction

This introduction is not part of IEEE Std 1277-2020, IEEE Standard for General Requirements and Test code for Dry-Type and Oil-Immersed Smoothing Reactors and for Dry-Type Converter Reactors for DC Power Transmission.

In 1986, the Transformers Committee of the Institute of Electrical and Electronic Engineers created the HVDC Converter Transformers and Smoothing Reactors Subcommittee. This committee developed from the working group that prepared paper 85 SM 375-1, “Recommended Dielectric Tests and Test Procedures for Converter Transformers and Smoothing Reactors.” Although smoothing reactors for HVDC application have been built and operated for over 30 years, prior to IEEE Std 1277™ there were only a limited number of papers, guides, and standards available that presented suggested dielectric tests for the HVDC equipment (see [Annex D](#) for a list of some of the most relevant documents). The IEC reactor standard IEC 60076-6:2007 [B10] also covers smoothing reactors in a specific clause; focus is not, however, application-specific.¹ With the increased activity in HVDC transmission, there was a significant need for a standard specifically covering the requirements and testing of smoothing reactors for HVDC applications, and the first responsibility of the new subcommittee was to create proposed standards for converter transformers and smoothing reactors for HVDC application. Two separate standards were developed—one for oil-filled converter transformers, and one for both dry-type and oil-filled smoothing reactors. IEEE Std 1277 was originally released in 2000 as “trial use” and, approximately two years later in 2002, was granted “full use” status.

The revision in 2020 was focused to upgrade test code, design considerations, and application information based on feedback from manufacturers and “end users”—dry-type or oil-immersed specific when required. The designation “oil-immersed” is kept, as at time of writing, smoothing reactors with alternative insulation liquid have not been available. Test code methodology has been modified to reflect current technology. The main purpose of this current revision is the introduction of the air-core dry-type converter reactors for the VSC (voltage sourced converter) HVDC schemes. Furthermore, the document has been cleaned up as, for example, oil-immersed smoothing reactors are rarely used in today’s HVDC schemes. As HVDC smoothing reactors according to this standard are used for all voltage levels, the present standard is also valid for so called UHVDC (ultra-high voltage direct current with nominal dc voltage of 800 kV and higher) applications.

¹The numbers in brackets correspond to those of the bibliography in [Annex D](#).

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IEEE Standard General Requirements and Test Code for Dry-Type and Oil-Immersed Smoothing Reactors and for Dry-Type Converter Reactors for DC Power Transmission

1. Overview

1.1 Scope

The scope of this standard is the definition and specification of the functional requirements and test code for dry-type and oil-immersed smoothing reactors and dry-type converter reactors for high-voltage direct current (HVDC) power transmission. This standard only applies to smoothing reactors for dc transmission and converter reactors for dc transmission located at the converter arms.

1.2 Purpose

The purpose of this standard is to provide those in the HVDC industry, manufacturers, and “end users” a document that defines and specifies the electrical, mechanical, and physical requirements of dry-type and oil-immersed smoothing reactors for HVDC applications. Furthermore, the document defines and specifies electrical, mechanical, and physical requirements of dry-type converter reactors used for voltage-sourced HVDC converters (VSC HVDC) that are located at the converter arms and loaded with dc and ac current. Test code is also defined and specified. Converter reactors are usually built in dry-type air-core and air-cooled design. Thus, only this type of converter reactor design is considered in this standard.

In addition, appropriate technical background information, that will facilitate the use of this standard, is presented or identified.

1.3 Word usage

The word *shall* indicates mandatory requirements strictly to be followed in order to conform to the standard and from which no deviation is permitted (shall equals is required to).^{2,3}

²The use of the word *must* is deprecated and cannot be used when stating mandatory requirements, *must* is used only to describe unavoidable situations.

³The use of *will* is deprecated and cannot be used when stating mandatory requirements, *will* is only used in statements of fact.

The word *should* indicates that among several possibilities one is recommended as particularly suitable, without mentioning or excluding others; or that a certain course of action is preferred but not necessarily required (should equals is recommended that).

The word *may* is used to indicate a course of action permissible within the limits of the standard (may equals is permitted to).

The word *can* is used for statements of possibility and capability, whether material, physical, or causal (can equals is able to).

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

ANSI C68.3-1976, American National Standard Recommended Practice for the Detection and Measurement of Partial Discharges (Corona) During Dielectric Tests.⁴

ASTM D1275, Standard Test Method for Corrosive Sulfur in Electrical Insulating Oils.⁵

IEC 60076-3, Power transformers—Part 3: Insulation levels, dielectric tests, and external clearance in air.⁶

IEC 60270, High-voltage test techniques—Partial discharge measurements.

IEC TR 62271-300, High-voltage Switchgear and Controlgear—Part 300: Seismic Qualification of Alternating Current Circuit-Breakers.

IEC/IEEE 65700-19-03, Bushings for DC Applications.

IEEE Std 4™, IEEE Standard Techniques for High Voltage Testing.^{7,8}

IEEE Std 315™, IEEE Standard Graphic Symbols for Electrical and Electronics Diagrams (Including Reference Designation Letters).

IEEE Std 693™, IEEE Recommended Practices for Seismic Design of Substations.

IEEE Std C57.12.00™-2015, IEEE Standard General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers.

IEEE Std C57.12.80™, IEEE Standard Terminology for Power and Distribution Transformers.

IEEE Std C57.12.90™-2015, IEEE Standard Test Code for Liquid-Immersed Distribution, Power, and Regulating Transformers.

⁴ANSI publications are available from the American National Standards Institute (<https://www.ansi.org/>).

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IEEE Std C57.16™, IEEE Standard for Requirements, Terminology, and Test Code for Dry-Type Air-Core Series-Connected Reactors.

IEEE Std C57.21™, IEEE Standard Requirements, Terminology, and Test Code for Shunt Reactors Rated Over 500 kVA.

IEEE Std C57.98™, IEEE Guide for Transformer Impulse Tests.

IEEE Std C57.113™, IEEE Guide for Partial Discharge Measurement in Liquid-Filled Power Transformers and Shunt Reactors.

NEMA 107-2016, Methods of Measurement of Radio Influence Voltage (RIV) of High- Voltage Apparatus.⁹

3. Definitions

For the purposes of this document, the following terms and definitions apply. Standard transformer terminology available in IEEE Std C57.12.80™ shall apply.¹⁰ The IEEE Standards Dictionary Online should be consulted for terms not defined in this clause.¹¹

ambient temperature: The ambient temperature is the temperature of the cooling air surrounding a smoothing reactor or converter reactor.

harmonic current:

- Smoothing reactor: The total harmonic current content superimposed on the dc current. For specific engineering purposes, it is essential to define the harmonic spectrum in terms of rms amplitude and frequency.
- Converter reactor: The total harmonic current content superimposed on the dc current and system frequency ac current. For specific engineering purposes, it is essential to define the harmonic spectrum in terms of rms amplitude and frequency.

incremental inductance: The incremental inductance of a smoothing reactor is the inductance of the smoothing reactor, in henries, determined on the basis of a small current increase (or decrease) at a pre-defined dc current. The incremental inductance is, therefore, defined as a function of dc current from the minimum current up to the maximum peak short-circuit current.

nominal inductance of a converter reactor: The nominal inductance of a converter reactor is the self-inductance at nominal system frequency.

nominal inductance of a smoothing reactor: The nominal inductance of a smoothing reactor is the incremental inductance seen by the ac current of a particular value and frequency superimposed on the direct current through the reactor. For a 12-pulse scheme, this frequency is 12 times the system frequency (e.g., 720 Hz for 60 Hz systems).

rated ac current of a converter reactor: The maximum continuous ac rms current at system frequency at rated conditions.

rated dc current of a smoothing reactor or converter reactor: The maximum continuous dc current at rated conditions.

⁹NEMA publications are available from the National Electrical Manufacturers Association (<https://www.nema.org/>).

¹⁰Information on references can be found in [Clause 2](#).

¹¹IEEE Standards Dictionary Online is available at: <http://dictionary.ieee.org>. An IEEE Account is required for access to the dictionary, and one can be created at no charge on the dictionary sign-in page.

rated ac voltage of a converter reactor: The rated ac voltage of a converter reactor is the maximum continuous ac rms voltage, terminal to ground, that will be experienced by the converter reactor.

rated dc voltage: The rated dc voltage of a smoothing reactor or converter reactor is the maximum continuous dc voltage, terminal to ground, that will be experienced by the reactor.

smoothing reactor (SMR) for HVDC transmission: A smoothing reactor for HVDC application is a reactor intended for connection in series with an HVDC converter, or an HVDC transmission line or insertion in the intermediate dc circuit of a back-to-back link, for the purpose of the following:

- Reducing harmonics in the dc line.
- Complying, in conjunction with dc filters, with the dc side telephone interference requirements.
- Limiting the surge-current amplitude during faults and disturbances, especially the limitation of cable discharge currents in the case of a long dc cable.
- Providing a high impedance to the flow of harmonics in the case of a cable link (high capacitance of cable).
- Limiting the rate of rise of inverter dc current in the case of inverter ac network disturbances, thus reducing the risk of commutation failures in case of LCC converters.
- Improving the dynamic stability of the dc transmission system (commutation failures in case of LCC converters).

Smoothing reactors may be built using either of two designs: dry-type air cooled or oil-immersed. Dry-type smoothing reactors are of air-core design. Oil-immersed smoothing reactors utilize magnetic-core materials as an inherent part of their design.

converter reactor for voltage sourced (VSC) HVDC transmission: A converter reactor for voltage sourced (VSC) HVDC application is a reactor intended for connection in series with the converter modules in the converter arms of a voltage sourced HVDC converter, for the purpose of the following:

- di/dt limitation for the converter modules during switching.
- Short circuit protection for the converter modules.
- Limiting the rate-of-rise of short circuit currents.
- Improving the controllability of the converter to balance the current between the converter arms.
- To provide sufficient reactance between the VSC converter and the ac network to allow a good controllability of the power and reactive power exchanges between the ac network and the converter.

NOTE—Converter reactors are to be distinguished from series reactors located at the ac side of 2- or 3- level converters. The purpose of these reactors, sometimes referred to as phase reactors is to accommodate the difference in voltage of the ac system that is virtually sinusoidal and the voltage at the ac terminals of the converter, which is typically non-sinusoidal. Other than converter reactors phase reactors do not carry dc current.¹²

4. Letter symbols

A	altitude
A_0	standard reference altitude of 1000 m

¹²Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.

E_{acMax}	maximum ac voltage (phase to phase) at the reactor
$E_{ac\ Applied}$	ac applied test voltage
E_{dc}	dc applied test voltage
E_{dcMax}	maximum dc voltage at the reactor
E_{PR}	polarity-reversal test voltage
E_r	resistance voltage component, in phase component
E_x	reactance voltage component, quadrature component
E_z	impedance voltage of winding carrying current
F	empirical factor used in calculating increase in temperature rise at altitude, A
f_h	harmonic frequency
h	harmonic number (order)
I_{dc}	rated dc current
I_{ac}	rated ac current (for converter reactors)
$I_{ac\ equiv}$	equivalent ac current
I_h	magnitude of current at harmonic, h
I_m	current in the reactor when losses are measured
I_r	rated current
$I_{reduced}$	reduced test current
I_{test}	dc test current
L_{PA}	average sound-pressure level (dB)
L_{PAi}	measured sound-pressure level at location, i (dB)
L_{WA}	sound-power level (dB)
N	number of measurement locations
P_a	watts measured in impedance test of winding carrying current
P_{fe}	core losses
P_h	harmonic losses of oil-immersed smoothing reactor (SMR) (including core losses) at harmonic frequency, h , and corrected to 85 °C
P_{htot}	sum of harmonic current losses (resistive plus eddy)
P_{LLG}	load loss used in determining guaranteed total losses
P_{LLT}	total load losses of oil-immersed SMR at T –85 °C
P_o	PR (ohmic) losses at rated current
P_r	losses at rated current
P_s	losses at reference temperature, T_s , and measured current, I_m
P_{TL}	total loss under service conditions (used for temperature-rise test)
R_{dc}	winding dc resistance corrected to reference temperature
R_h	resistive component of the impedance at harmonic frequency, f_h

R_m	measured resistance
R_s	resistance at desired temperature, T_s
S	measurement surface area (sound power) (m^2)
T_a	ambient air temperature ($^{\circ}\text{C}$)
T_m	temperature at which resistance is measured
T_s	desired reference temperature
X_h	reactance component of the impedance at harmonic frequency
Z_h	impedance at harmonic frequency, f_h
θ	temperature ($^{\circ}\text{C}$)
θ'	measured temperature ($^{\circ}\text{C}$)

5. General requirements—Systems and environmental data

5.1 Usual service conditions

5.1.1 General

Smoothing reactors and converter reactors conforming to this standard shall be suitable for operation at currents as per 6.3.2 and as per 7.3.3 under the usual service conditions defined in 5.1.2 to 5.1.4.

5.1.2 Temperature

When air is the cooling medium, the temperature of the cooling air (see “ambient temperature” in [Clause 3](#)) shall not exceed 40 $^{\circ}\text{C}$, and the average temperature of the cooling air for any 24 h period shall not exceed 30 $^{\circ}\text{C}$. The usual minimum ambient temperature is considered to be -40°C .

Converter reactors are also often installed indoors under a controlled environment. Such service conditions need to be specified in detail, particularly, the long-term ambient temperature profile may differ significantly due the control of heat exchange in the converter reactor room. Also, the maximum ambient temperature may exceed 40 $^{\circ}\text{C}$. In addition to the temperature profile, the associated minimum humidity shall be specified. Such cases should be described as unusual service conditions, and full details shall be provided in the reactor specification.

The case of oil-immersed smoothing reactors operating with bushings projecting into a valve hall, where ambient temperatures exceed 40 $^{\circ}\text{C}$, does not constitute an unusual operating condition for the smoothing reactor. The valve hall maximum temperature and minimum humidity shall only be specified as an unusual service condition for the internal and external insulation of the bushing.

5.1.3 Altitude

The altitude shall not exceed 1000 m.

5.1.4 Installation location

Outdoor installation is the usual operating environment. However, converter reactors are frequently installed indoors.

5.2 Unusual service conditions

Conditions other than those described in 5.1 are considered unusual service, and when prevalent these conditions should be brought to the attention of those responsible for the design and application of the apparatus.

5.2.1 Unusual ambient temperature conditions

The temperature-rise limits of reactors should be adjusted if the cooling air ambient temperature exceeds the limits described in 5.1.2. If the cooling air ambient temperature at site exceeds either of the limits, then the specified temperature-rise limits for the reactor shall be reduced by the same amount as the excess. The adjusted temperature-rise limits shall be rounded to the nearest whole number of degrees Celsius.

Minimum ambient temperatures below -40°C should be specified as they may have an impact on the reactor.

If a particular current rating versus ambient temperature performance is required without additional loss of life, this shall be clearly defined in the specification.

For indoor reactors, the ambient temperature inside the reactor hall usually exceeds the limits described in 5.1.2. Higher ambient air temperature results in lower air density that contributes to reduce the dielectric withstand of air insulation. Thus, the specified dielectric withstand voltages shall be associated with the reactor hall ambient air conditions (e.g., maximum air temperature and associated minimum air humidity).

If dielectric tests are performed at usual laboratory ambient air conditions, correction factors shall be applied to test voltages in order to take into account the most stringent ambient conditions prevailing in the reactor hall. Correction factors shall be calculated according to the methodology defined in IEEE Std 4™.

NOTE—Smoothing and converter reactors may be uniquely (custom) specified and designed for a specific location and set of operating conditions and, therefore, loading versus ambient temperature condition may be the norm. Establishing a current rating versus ambient temperature, etc., involves a number of considerations such as the thermal capability of the insulation system versus the winding operating temperature under rated conditions. This may be affected by a significant loss evaluation or other aspects of the specification, which reduces the temperature rise of the winding below the insulation system thermal capabilities.

5.2.2 Unusual altitude conditions

5.2.2.1 Effect of altitude on insulation

For both oil-immersed and dry-type smoothing reactors, as well as for dry-type converter reactors, the dielectric strength, which depends in whole or in part upon air for insulation, decreases as the altitude increases because of decreased air density. In the case of dry-type reactors, the encapsulated windings depend in part on air for dielectric strength, and the support insulators depend in total on air for dielectric strength. For oil-immersed smoothing reactors, the bushings depend in part on air for dielectric strength. If dielectric margins are adjusted in the specification to accommodate the operation of the smoothing reactor at a higher altitude, the dielectric test levels shall be as specified. Otherwise, for dry-type reactors specified for operation at altitudes between 1000 m and 3000 m above sea level, but tested at normal altitude, the test voltages for external insulation (air insulation) shall be increased using the correction factors from Table 1 in IEEE Std C57.12.00™-2015. For oil-immersed smoothing reactors, the bushings shall be tested at an appropriately increased test level, but the windings shall be tested at nominal value. In the case of dry-type reactors, both the insulators and windings shall be tested at the appropriate higher voltage. In any case, the purchaser's specification shall state if the specified test levels have taken the higher operating altitude into account.

5.2.2.2 Effect of altitude on temperature rise

Smoothing and converter reactors for HVDC application are custom designed to meet the HVDC system operating requirements and the site conditions. Therefore, units to be installed at sites with an altitude in excess of 1000 m, but tested at normal altitude, shall have their maximum temperature-rise limits adjusted as follows:

- Oil-immersed reactors: For a naturally cooled reactor (ONAN), the limit of the average winding temperature rise shall be reduced by 1 °C for every interval of 400 m by which the installation's altitude exceeds 1000 m. For a forced-cooled oil-immersed smoothing reactor, the reduction shall be 1 °C for every 250 m.
- Dry-type air-core reactors: Unless otherwise agreed between the manufacturer and the purchaser, for units designed for operation at an altitude greater than 1000 m but tested at normal altitudes, the limits of temperature rise given in [Table 4](#) are reduced by 2.5% for each 500 m by which the intended working altitude exceeds 1000 m.

The following requirements are applicable to both oil-immersed and dry-type reactors:

- a) A corresponding reverse correction may be applied in cases where the altitude of the factory is above 1000 m and the altitude of the installation site is below 1000 m.
- b) Any altitude correction shall be rounded to the nearest whole number of degrees Celsius.
- c) When the specific temperature-rise limits of the equipment have been reduced, either because of high cooling media temperature or because of high-altitude installation, this shall be indicated on the rating plate.

5.2.3 Loading at other than rated conditions

Loading of a smoothing or converter reactor at other than rated current is a common operating practice for most HVDC projects.

If the reactor is to be operated at various loading conditions including possible overload for a specific duration, these conditions including their duration and the respective allowable temperature rises shall be included in the specification for the reactor.

5.2.4 Seismic conditions

HVDC converter stations may be located in areas at significant risk of being affected by seismic activity. Therefore, the appropriate seismic zone/category from IEEE Std 693™ or other equivalent international guidelines (e.g., IEC/TR 62271-300) shall be indicated in the specification.

5.2.5 Other unusual service conditions

In addition to the usual service conditions previously described, the following may also constitute unusual service conditions for smoothing reactors or converter reactors in HVDC applications:

- a) Damaging fumes or vapors, excessive or abrasive dust, explosive mixtures of dust or gases, steam, salt spray, excessive moisture, etc., constitute unusual service conditions. Pollution aspects are important and shall be accurately defined so that proper external insulation (particularly bushings and support insulators) may be provided. Pollution includes automotive, acid rain (conductivities in the range of 1000 µS/cm to 3000 µS/cm versus less than 100 µS/cm for normal rain) fertilizers, road salt, oceanic salt, etc.

- b) Equivalent salt deposition density (ESDD) rates and creepage requirements should always be specified for bushings and other external insulation.
- c) Installation conditions that may affect the operating temperature of the reactor include station layout (clearances), lack of air movement, solar radiation based heating of ground cover, etc.
- d) Indoor installation in a high ambient temperature that may be continuously high.
- e) Unusual limitations for transportation should always be specified, especially since smoothing reactors, and to some extent converter reactors, are large, heavy pieces of equipment. Unusual storage conditions (heavy moisture exposure) or duration of storage prior to installation (greater than one year) should be specified.
- f) Maintenance restrictions should be specified, especially if time between maintenance is longer than one year, or if it is not possible to perform periodic inspections.
- g) Other unusual voltage conditions, including transient overvoltages, resonance, switching surge, etc., which may require special consideration in insulation design.
- h) Expected severity of short circuits as part of regular operation or as a consequence of relaying practice and unusual short-circuit application conditions differing from those described in 12.8.
- i) Unusual number of line faults (> 30 per year) or commutation failures (> 50 per year).
- j) Unusual harmonic current content.

5.3 Environmental impact—Oil-immersed smoothing reactors

The impact on the environment shall be considered in the use of materials contained within oil-immersed smoothing reactors. Gasket materials shall be chosen and accelerated-aging tested to demonstrate a long life, and thus reduce oil leaks.

5.4 Synthetic materials—Oil-immersed smoothing reactors

The use of synthetic materials such as plastics is increasing. Compatibility with oil, high temperatures, and other material is required. Accelerated-aging tests are required to prove the materials will last the specified life of the oil-immersed smoothing reactor.

5.5 Insulation liquid—Oil-immersed smoothing reactors

5.5.1 Non-corrosive oil

The transformer oil used in HVDC smoothing reactors shall fulfill the criteria for non-corrosive oil in accordance with the extended ASTM test in ASTM D1275–2015, Method B. See also other supporting documents in Annex D: Hajek [B8], Wiklund [B19], and CIGRÉ [B1].¹³

5.5.2 Synthetic and non-mineral insulation oils

Synthetic and non-mineral insulating oils are now available. Little information is available regarding their applicability/usage in oil-immersed smoothing reactors.

5.6 Bushings—Oil-immersed smoothing reactors

The bushings shall be designed and tested according to IEC/IEEE 65700-19-03.

¹³The numbers in brackets correspond to those of the bibliography in Annex D.

NOTE—DC bushings in general have more insulation than ac bushings. In addition, the oil immersed portion at higher voltages (generally over 200 kV) is designed such that they form an integral part of the insulation structure of the reactor. As such, they are not interchangeable with other dc bushings with similar ratings, and only those bushings specifically designed and tested with the particular insulation structure can be expected to work as replacements.

5.7 Design and construction—Oil-immersed smoothing reactors

Oil-immersed smoothing reactors are nowadays widely replaced by air-core dry-type smoothing reactors. Therefore, no separate section for design and construction details of oil-immersed smoothing reactors is now included in this standard. The construction shall follow the principles as per IEEE Std C57.12.10™ if not stated otherwise in this standard.

6. Rating data of smoothing reactors

6.1 Basis for rating

The rating of a smoothing reactor shall be expressed in the following terms:

- a) Rated dc voltage
- b) Rated dc current
- c) Harmonic current spectrum
- d) Rated incremental inductance
- e) Basic lightning impulse insulation levels (across terminals and to ground)
- f) Oil and/or winding temperature rise
- g) Method of cooling
- h) Switching impulse level(s) (across the terminals and to ground)
- i) Short-circuit current or surge current

6.2 Rated dc voltage

The rated dc voltage of a smoothing reactor is the maximum continuous dc voltage, terminal-to-ground, that will be experienced by the smoothing reactor.

6.3 Rated currents

6.3.1 Rated dc current

The rated dc current of a smoothing reactor is the maximum continuous dc current at rated conditions.

6.3.2 Rated dc current plus harmonics

Smoothing reactors shall be designed for operation with rated dc current plus harmonics.

6.3.3 Rated dc overload current

Several values may be specified, including 1 h maximum in a 24 h period, dc peak surge, low ambient overload, and redundant cooling (oil-immersed smoothing reactors only) overload. A time limit, usually in milliseconds, should be provided with the dc peak surge current. If not specified, this time limit should be considered to be 1 s. Allowable temperature rises and conditions should also be specified. See [Annex C](#) for more information.

The dc peak surge current can be the result of a converter side-line fault or a fault on the line side of the smoothing reactor. Thus, the characteristics of the fault current are different and should be specified and described by the purchaser. System design will play a role in defining the surge current parameters (peak, wave shape, duration, and frequency of occurrence).

6.4 Inductance

6.4.1 Rated incremental inductance

For iron-cored reactors operated well below magnetic saturation and air-cored reactors, the inductance is considered to be independent of current. Therefore, the rated inductance of a smoothing reactor is the inductance in henries, determined with low frequency (≤ 100 Hz) ac excitation.

For iron-cored reactors operated close to or beyond magnetic saturation of the core, the inductance is a function of current. In this case, the inductance of a smoothing reactor shall be defined by its incremental inductance. The rated inductance of a smoothing reactor in henries is the incremental inductance at rated continuous dc current.

6.4.2 Minimum inductance

A minimum inductance shall be maintained over the full operational range of dc plus harmonic current (at harmonic frequency) superimposed. The value of inductance is important to limit harmonic current and the amplitude of fault current. For oil-immersed iron-core smoothing reactors, the minimum incremental inductance shall be defined as a function of the dc current from zero up to the maximum fault current.

6.4.3 Tolerances

The tolerances on inductance apply from zero to maximum specified overload dc current. In the case of oil-immersed smoothing reactors, the degree of linearity should be defined from zero to maximum specified overload dc current. The minimum inductance value and minimum incremental inductance at rated short-circuit current shall also be specified. For dry-type air-core smoothing reactors, only a single tolerance on inductance shall be specified.

6.5 Basic impulse insulation level

6.5.1 Coordination of insulation levels

The specified basic impulse insulation level (BIL) and switching impulse levels at the smoothing reactor terminals to ground and across the smoothing reactor shall be such that the lightning impulse, chopped-wave impulse, and switching impulse insulation levels include a suitable margin in excess of the dielectric stresses to which the smoothing reactor can be subjected to in actual service. The insulation margins are typically not less than 20% for lightning impulse and not less than 15% for switching impulse voltages. CIGRÉ [B7] provides good information on insulation coordination. It should be noted that surge arresters used on dc systems are special designs. Additional information is included in A.9. The bibliography in Annex D also contains other useful resources like IEC 60071-5. For the winding of smoothing reactors, BIL shall be specified for each terminal to ground and across the winding. A different BIL can be specified across the winding than for each terminal to ground. The chopped-wave insulation level shall be determined by multiplying the respective BIL insulation level(s) by 1.1.

The winding shall also be designed for the switching impulse insulation level (SIL). A SIL shall be specified for each terminal to ground and across the winding. A different SIL can be specified across the winding than for each terminal to ground depending on system studies.

Very often for HVDC systems, there is no fixed standard ratio between the SIL and the lightning impulse insulation level as for ac systems (e.g., SIL = 83% of BIL). The reason is that each HVDC switchyard is custom designed and this makes it possible to control the BIL levels. Therefore, the SIL is very often the main insulation design criteria.

Insulation coordination practice shall be taken into consideration when retesting installed (old) smoothing reactors that have been repaired. The common practice for power transformers is based on 10.1.7 of IEEE Std C57.12.90™-2015. Installed (old) equipment is tested with 85% of full test voltage. For dc equipment, this may be below the arrester protective level, which is not reasonable. It is thus recommended to test installed (old) equipment with impulse test voltages corresponding, as a minimum, to 10% above the arrester protective levels. Therefore, the lightning impulse protective level (LIPL) and switching impulse protective level (SIPL) shall be specified, as well as the lightning impulse withstand level (LIWL) and switching impulse withstand level (SIWL) levels.

6.6 Cooling classes

6.6.1 Cooling classes of oil-immersed smoothing reactors

For cooling classes of oil-immersed smoothing reactors refer to IEEE Std C57.12.00-2015.

6.6.2 Cooling classes of dry-type smoothing reactors

Dry-type smoothing reactors are self-cooled by natural air convection; class AN.

6.7 Other requirements

6.7.1 Loss capitalization rates

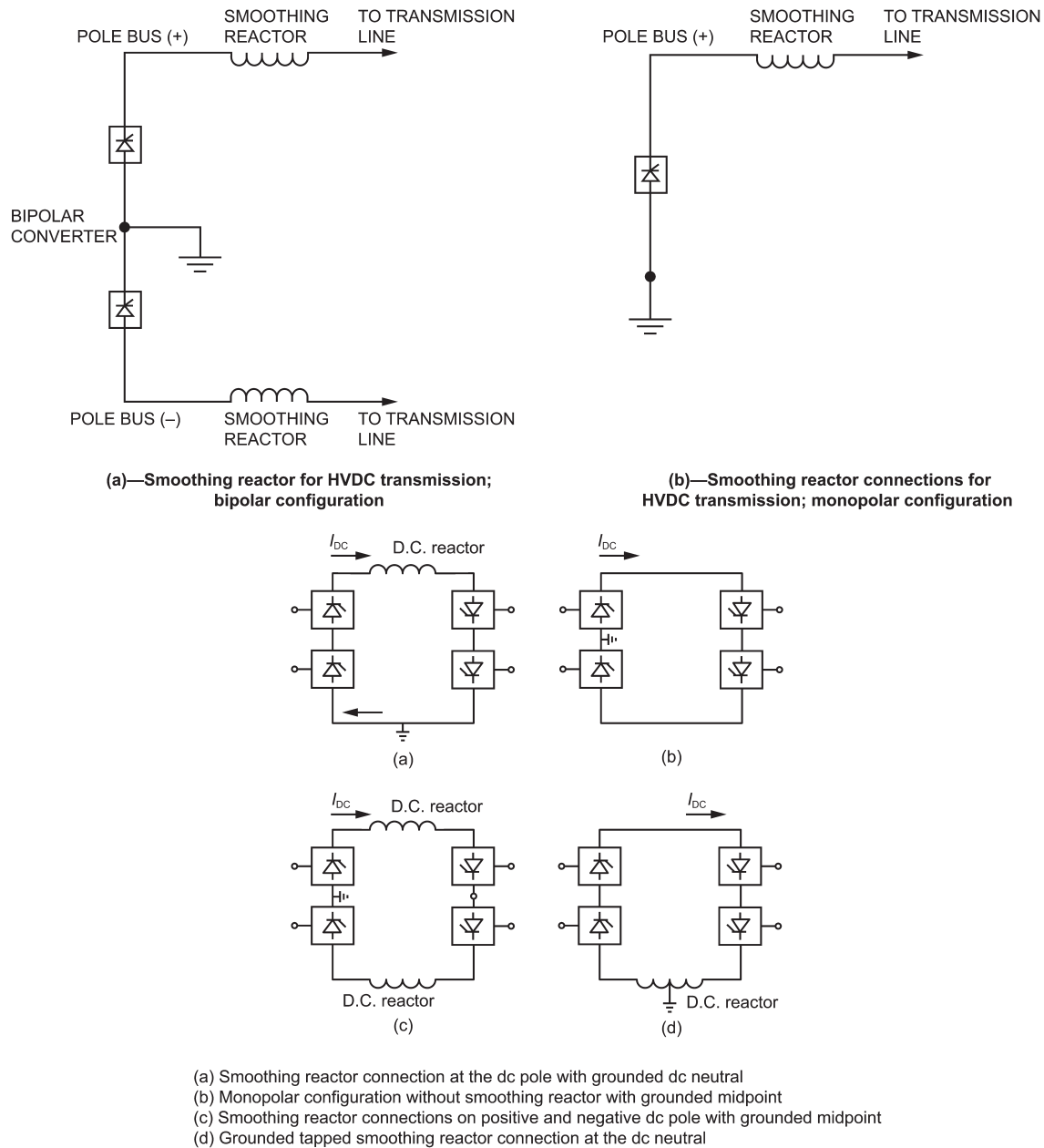
Loss capitalization rates, if applicable, should be provided by the purchaser to allow the manufacturer to optimize the design of the smoothing reactor for the specific application.

6.7.2 Audible sound level limits

Sound level limits, if required, shall be specified by the purchaser. Sound level is based on the applied current spectrum: dc current plus harmonic currents. The purchaser also shall specify the dc current plus harmonic current spectra for which the audible sound level performance requirements are to be fulfilled. Primary sources of sound level in an SMR are the result of the interaction of the static dc magnetic field with winding conductors carrying ripple harmonics. Thus, the major sound level spectrum is at the discrete frequencies of the harmonic ripple current.

6.7.3 Typical connections

Typical connections for smoothing reactors are presented in [Figure 1\(a\)](#), [Figure 1\(b\)](#), and [Figure 1\(c\)](#). They are bipolar, monopolar, and back-to-back. It should be noted that for a few back-to-back schemes, the commutation inductance of the converter transformers has been designed to provide an equivalent smoothing inductance, sufficient to provide the necessary smoothing of the dc current in the link without the need of adding a separate smoothing reactor.



(c)—Smoothing reactor connections for “back-to-back” converters:
sample configurations

Figure 1—Typical connection schemes for smoothing reactors

7. Rating data of converter reactors

7.1 Basis for rating

The rating of a converter reactor shall be expressed in the following terms:

- a) Rated dc voltage
- b) Rated dc current

- c) Rated ac voltage
- d) Rated ac current
- e) Rated system frequency
- f) Harmonic current spectrum
- g) Rated inductance
- h) Basic lightning impulse insulation levels (across terminals and to ground)
- i) Winding temperature rise
- j) Method of cooling
- k) Switching impulse level(s) (across the terminals and to ground)
- l) Short-circuit current or surge current

7.2 Rated dc voltage

The rated dc voltage of a converter reactor is the maximum continuous dc voltage, terminal-to-ground, that will be experienced by the converter reactor.

NOTE—The dc voltage of the converter reactor depends on its position relative to the converter valves (ac side or dc side reactors) and the topology of the scheme (bipole, symmetric monopole, asymmetric monopole, etc.).

7.3 Rated currents

7.3.1 Rated dc current

The rated dc current of a converter reactor is the maximum continuous dc current at rated conditions.

NOTE—The dc current of a converter reactor is about one third of the dc line current.

7.3.2 Rated ac current

The rated ac current of a converter reactor is the maximum continuous ac current at rated conditions.

NOTE—The ac current of a converter reactor is about half of the current at the ac terminals of the converter.

7.3.3 Rated currents plus harmonics

Converter reactors shall be designed for operation with rated dc current plus rated ac current plus harmonics.

7.4 Inductance

7.4.1 Rated inductance

For air-cored reactors the inductance is considered to be independent of current. Therefore, the rated inductance of a converter reactor is the inductance in henries, determined with ac excitation at fundamental frequency of the system.

7.4.2 Tolerances

The tolerances on inductance apply from zero to maximum specified current.

7.5 Basic impulse insulation level

7.5.1 Coordination of insulation levels

The BIL and SIL at the converter reactor terminals and across the converter reactor shall be such that the lightning impulse, chopped-wave impulse, and switching impulse insulation levels include a suitable margin in excess of the dielectric stresses to which the converter reactor can be subjected to in actual service. The insulation margins are typically not less than 20% for lightning impulse and not less than 15% for switching impulse voltages. For the winding of converter reactors, BIL shall be specified for each terminal to ground and across the winding. The winding shall also be designed for the SIL. An SIL shall be specified for each terminal to ground and across the winding. A different BIL/SIL can be specified across the winding than for each terminal to ground depending on system studies.

Very often for HVDC systems, there is no fixed standard ratio between the SIL and the lightning impulse insulation level as for ac systems (e.g., $SIL = 83\%$ of BIL). The reason is that each HVDC switchyard is custom designed and this makes it possible to control the BIL levels. Therefore, the SIL is often the main insulation design criteria.

7.6 Cooling classes

Dry-type converter reactors are self-cooled by natural air convection; class AN.

7.7 Other requirements

7.7.1 Loss capitalization rates

Loss capitalization rates, if applicable, should be provided by the purchaser to allow the manufacturer to optimize the design of the converter reactor for the specific application.

7.7.2 Audible sound level limits

Sound level limits, if required, shall be specified by the purchaser. Sound level is based on the applied current spectrum. The purchaser also shall specify a current spectrum for which the audible noise level performance requirements are to be fulfilled.

7.7.3 Typical connections

The scheme of a VSC HVDC converter in modular multilevel converter (MMC) technology is shown in [Figure 2](#) and [Figure 3](#).

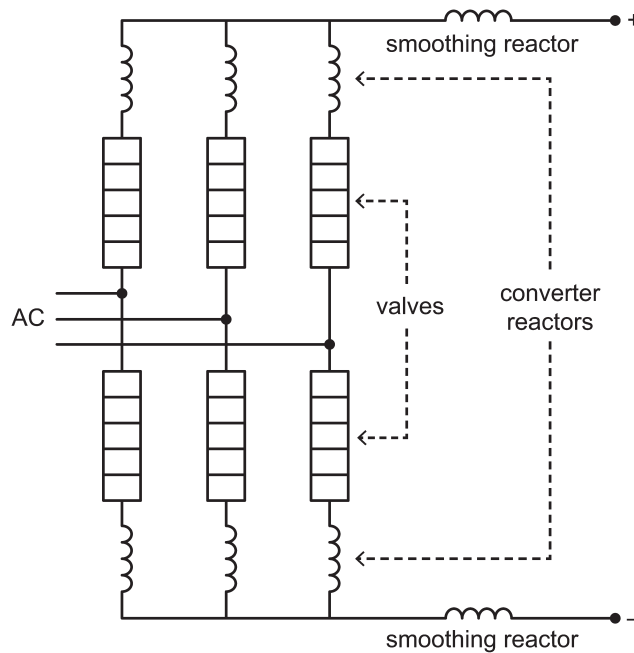


Figure 2—Converter reactor connected to the dc side of the valves

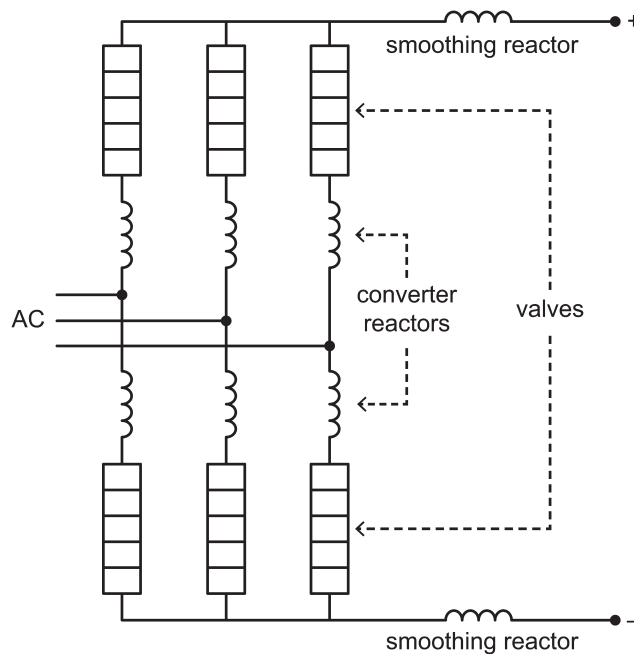


Figure 3—Converter reactor connected to the ac side of the valves

8. Tests

8.1 General

Unless otherwise specified, tests shall be made at the factory or in a test laboratory prior to delivery.

8.2 Routine, design, and other tests

Types of tests for oil-immersed smoothing reactors are listed in [Table 1](#). Types of tests for dry-type smoothing reactors are listed in [Table 2](#), and dry-type converter reactors are listed in [Table 3](#).

NOTE—Other tests are only performed when specifically requested by a purchaser.

8.2.1 Types of tests

8.2.1.1 Routine tests

Routine tests shall be made on all reactors of a multiple-unit order in accordance with the requirements of [Table 1](#), [Table 2](#), and [Table 3](#) as applicable.

8.2.1.2 Design tests

Design tests, unless otherwise agreed between the purchaser and the manufacturer, shall be made on one smoothing or converter reactor (of a specific design) of a multiple-unit order, in accordance with the requirements, as applicable. Test reports documenting the results of a previous test on a smoothing reactor or converter reactor of a demonstrated similar design may be submitted for consideration by the purchaser in lieu of performing a design test.

8.2.1.3 Other tests

Other tests as shown in [Table 1](#), [Table 2](#), and [Table 3](#), as applicable, shall be performed on either one or all smoothing reactors of a multiple-unit order as specified by the purchaser. Usually other tests are specified as design tests. Test reports documenting the results of a previous test carried out on a reactor of a demonstrated similar design may be submitted for consideration by the purchaser in lieu of performing another design test.

8.2.2 Test sequence

8.2.2.1 General

The listing of tests does not indicate the sequence in which the tests shall be made. All tests are defined and shall be made in accordance with [Clause 12](#).

For type tests on the reactors, the losses measurement and temperature-rise tests shall be performed before all routine dielectric tests.

8.2.2.2 Oil-immersed smoothing reactors

For oil-immersed smoothing reactors, the routine test sequence shall be such that the last dielectric tests to be performed shall be the ac applied test with partial discharge measurement followed by the ac power test with Q factor measurement. The sequence of remaining required routine tests is left to the convenience of the manufacturer.

Other tests for oil-immersed smoothing reactors may be performed at the convenience of the manufacturer, unless otherwise indicated in [Clause 12](#). For instance, the chopped-wave impulse test, if required, shall be performed within the lightning impulse test sequence as prescribed in [12.5](#).