



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

IEEE Power & Energy Society

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Transformers Committee

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Abstract: The electrical, mechanical, and physical requirements of oil-immersed and dry-type air-core smoothing 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, dry-type air-core, HVDC, oil-immersed, rating, smoothing reactors, test code application

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Introduction

This introduction is not part of IEEE Std 1277-2010, IEEE Standard General Requirements and Test Code for Dry-Type and Oil-Immersed Smoothing 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 G of this standard for a list of some of the most relevant documents). The IEC reactor standard IEC 60076-6:2007 [B9] also covers smoothing reactors in a specific clause; focus is not, however, application-specific.^a 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.

Significant accomplishments of IEEE Std 1277-2000 included:

- a) Establishment of dielectric tests on HVDC equipment. In addition to the polarity reversal and 1 h dc tests recommended by previous papers, a special 1 h ac-applied voltage test was included for oil-filled smoothing reactors to demonstrate insulation integrity for service conditions.
- b) A consistent test methodology was developed for both oil-immersed and dry-type air-core smoothing reactors that reflects both in-service operating stresses as well as current test equipment capability.

The purpose of this current revision is the same as the original document, which is to define requirements and test code for dry-type and oil-immersed smoothing reactors for HVDC application. Although requirements are usually construction independent, test code is not, and the revision of the standard will continue to reflect this characteristic. This revision is required 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. Test code methodology has been modified to reflect current technology.

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^a The numbers in brackets correspond to those of the bibliography in Annex G.

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1. Scope

The scope of this standard is the definition and specification of the requirements and test code for dry-type and oil-immersed smoothing reactors for high-voltage direct current (HVDC) power transmission. This standard only applies to smoothing reactors for dc transmission. It does not apply to other smoothing reactors such as reactors for power converters for variable speed drives, etc.

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.¹

ANSI S1.4-1983, American National Standard Specification for Sound Level Meters.

¹ ANSI publications are available from the Customer Service Department, American National Standards Institute, 25 W. 43rd Street, 4th Floor, New York, NY 10036, USA (<http://www.ansi.org/>).

ANSI/ASME B1.1-1989, American National Standard Unified Inch Screw Threads (UN and UNR Thread Forms).²

ANSI/ASME B1.1a-1984, Unified Inch Screw Threads (UN and UNR Thread Form) Supplement to ANSI B1.1-1982.

ANSI/ASME B1.20.1-1983, Pipe Threads, General Purpose (Inch).

ANSI/ASME Boiler and Pressure Vessel Code (BPV), 1984 Edition.

ASTM D1275-2006, Standard Test Method for Corrosive Sulfur in Electrical Insulating Oils.³

ASTM D3487-1981, Standard Specifications for Mineral Insulating Oil Used in Electrical Apparatus.

IEC 60076-3:2000, Power transformers—Part 3: Insulation levels, dielectric tests, and external clearance in air.⁴

IEC 60270:2001, High-voltage test techniques—Partial discharge measurements.

IEC/TS 61245:1993, Artificial pollution tests on high-voltage insulators to be used on dc systems.

IEEE Std 4TM-1995, IEEE Standard Techniques for High Voltage Testing.^{5, 6}

IEEE Std 315TM-1975 (Reaff 1993), IEEE Standard Graphic Symbols for Electrical and Electronics Diagrams (Including Reference Designation Letters).

IEEE Std 315ATM-1986, Supplement to IEEE Std 315-1975.

IEEE Std 693TM-2005, IEEE Recommended Practices for Seismic Design of Substations.

IEEE Std C57.12.00TM-2006, IEEE Standard General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers.

IEEE Std C57.12.80TM-2002, IEEE Standard Terminology for Power and Distribution Transformers.

IEEE Std C57.12.90TM-2006, IEEE Standard Test Code for Liquid-Immersed Distribution, Power, and Regulating Transformers.

IEEE Std C57.16TM-1996 (Reaff 2001), IEEE Standard Requirements, Terminology, and Test Code for Dry-Type Air-Core Series-Connected Reactors.

IEEE Std C57.19.03TM-1996, IEEE Standard Requirements, Terminology, and Test Code for Bushings for DC Applications.

² ASME publications are available from the American Society of Mechanical Engineers, 3 Park Avenue, New York, NY 10016-5990, USA (<http://www.asme.org/>).

³ ASTM publications are available from the American Society for Testing and Materials, 100 Barr Harbor Drive, West Conshohocken, PA 19428-2959, USA (<http://www.astm.org/>).

⁴ IEC publications are available from the Central Office of the International Electrotechnical Commission, 3, rue de Varembe, P.O. Box 131, CH-1211, Geneva 20, Switzerland (<http://www.iec.ch/>). IEC publications are also available in the United States from the Sales Department, American National Standards Institute, 25 West 43rd Street, 4th Floor, New York, NY 10036, USA (<http://www.ansi.org/>).

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IEEE Std C57.98™-1993 (Reaff 1999), IEEE Guide for Transformer Impulse Tests.

IEEE Std C57.106™-2006, IEEE Guide for Acceptance and Maintenance of Insulating Oil in Equipment.

IEEE Std C57.113™-1991 (Reaff 2002), IEEE Guide for Partial Discharge Measurement in Liquid-Filled Power Transformers and Shunt Reactors.

NEHRP-1997, National Earthquake Hazards Reduction Program, Recommended Provisions for Seismic Regulations for New Buildings [Federal Emergency Management Agency (FEMA), 1997].⁷

NEMA CC1-2009, Electric Power Connection for Substations.⁸

3. Definitions

Standard transformer terminology available in IEEE Std C57.12.80-2002 shall apply.⁹ *The IEEE Standards Dictionary: Glossary of Terms & Definitions* should be referenced for terms not defined in this clause.¹⁰

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

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.

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

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.

ripple current: The total harmonic current content superimposed on the dc current. For specific engineering purposes, it is essential to define the harmonic spectrum of the ripple current in terms of amplitude and frequency. For general purposes, the ripple current can be expressed as the root-mean-square (rms) value of the harmonic current at any level of dc current; including the continuous rated dc current.

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).

⁷ NEHRP publications are available from the Building for Seismic Safety Council, 1201 L St., N.W., Suite 400, Washington, D.C. 20005, USA.

⁸ NEMA publications are available from Global Engineering Documents, 15 Inverness Way East, Englewood, Colorado 80112, USA (<http://global.ihs.com/>).

⁹ Information on references can be found in Clause 2.

¹⁰ *The IEEE Standards Dictionary: Glossary of Terms & Definitions* is available at <http://shop.ieee.org/>.

- Limiting the rate of rise of inverter dc current in the case of inverter ac network disturbances, thus reducing the risk of commutation failures.
- Improving the dynamic stability of the dc transmission system (commutation failures).

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.

4. Letter symbols

A	altitude
A_o	standard reference altitude of 1000 m
E_{ac}	ac voltage
$E_{acApplied}$	ac applied test voltage
E_{dc}	dc applied test voltage
$E_{dcSystem}$	maximum dc rated voltage of system
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_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
$I_{ac equiv.}$	equivalent ac 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_{fctor}	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	I^2R (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 (°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 (°C)
θ'	measured temperature (°C)

5. General requirements—Systems and environmental data

5.1 Usual service conditions

5.1.1 General

Smoothing reactors conforming to this standard shall be suitable for operation at rated current (dc plus harmonics) under the usual service conditions defined as follows.

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 °C and the average temperature of the cooling air for any 24 h period shall not exceed 30 °C. The usual minimum ambient temperature is considered to be –40 °C.

The case of oil-immersed smoothing reactors operating with bushings projecting into a valve hall, where ambient temperatures exceed 40 °C, does not constitute an unusual operating condition for the smoothing

reactor. The valve hall temperature should 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 for smoothing reactors.

5.2 Unusual service conditions

Conditions other than those described in 5.1 are considered unusual service and when prevalent 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 oil-immersed and dry-type air-core smoothing 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 oil-immersed or dry-type air-core smoothing 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 smoothing reactor.

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

NOTE 1—Smoothing 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 aspect of the specification, which reduces the temperature rise of the winding below the insulation system thermal capabilities.¹¹

NOTE 2—Since the thermal time constant for smoothing reactors of high-power rating may be large, reduction of the temperature rise to accommodate operation at maximum ambient temperatures higher than 40°C may only be required when the time at ambient above 40°C is greater than 50% of the reactor thermal time constant.

¹¹ Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.

5.2.2 Unusual altitude conditions

5.2.2.1 Effect of altitude on insulation

For both oil-immersed and dry-type smoothing reactors, the dielectric strength, which depends in whole or in part upon air for insulation, decreases as the altitude increases due to the effect of decreased air density. In the case of dry-type smoothing 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 smoothing 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 C57.12.00-2006. For oil-immersed smoothing reactors, the bushing shall be tested at an appropriately increased test level, but the windings shall be tested at nominal value. In the case of dry-type smoothing 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 reactors for HVDC application are custom designed to meet the HVDC system operating requirements and the site conditions. Therefore, smoothing reactors 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 smoothing 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 smoothing reactors: Unless otherwise agreed between the manufacturer and the purchaser, for smoothing reactors designed for operation at an altitude greater than 1000 m but tested at normal altitudes, the limits of temperature rise given in Table 3 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 smoothing 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 smoothing reactor 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 reactor at other than rated current is a normal part of smoothing reactor operating practice for most HVDC projects. Smoothing reactors are normally designed for a specific converter station and are coordinated with the design of the valves, converter transformers, and other dc components. Examples of typical overloads include: low ambient temperature overload, emergency overload, monopolar

operation following the loss of one pole, continuous overload with redundant coolers available (oil-immersed smoothing reactors only), 1 h or 2 h overload, temporary overload for a duration of minutes or seconds, etc.

If the smoothing reactor is to be operated at various loading conditions (dc plus harmonics), these conditions and the respective allowable temperature rises shall be included in the specification for the smoothing 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 693-2005 and NEHRP-1997 or other equivalent international seismic standard shall be indicated in the smoothing reactor 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 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. For smoothing reactors, 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 $\mu\text{S}/\text{cm}$ to 3000 $\mu\text{S}/\text{cm}$ versus less than 100 $\mu\text{S}/\text{cm}$ for normal rain) fertilizers, road salt, oceanic salt, etc. Annex A and Annex B contain additional information on pollution.
- 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 smoothing 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 are large, heavy pieces of equipment. Unusual storage conditions (heavy moisture exposure) or duration of storage prior to installation (greater than 1 year) should be specified.
- f) Maintenance restrictions should be specified, especially if time between maintenance is longer than 1 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. For instance, if smoothing reactors are connected to SF_6 insulated equipment, there may be risks of exposure to very fast voltage transients.
- h) Planned 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 (ripple) 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 minimize 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 Transformer oil—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 D1275-2006 Method B. See also other supporting documents in Annex G: Hajek [B6], Wiklund [B23], CIGRÉ [B3].¹²

NOTE—CIGRÉ W.G. A2-32 is, among other tasks, developing tests for transformer oil.

5.5.2 Synthetic and insulation oils

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

6. Rating data

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

¹² The numbers in brackets correspond to those of the bibliography in Annex G.

- 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-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 D 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 inductance

For air-cored reactors and iron-cored reactors operated well below magnetic saturation, 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 maximum specified overload dc 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 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. Background information on smoothing reactor insulation coordination is provided in A.2. CIGRÉ [B4] 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.2 and B.9. The bibliography in Annex G also contains other useful resources. 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). An 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 C57.12.90-2006. 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

6.6.1.1 Oil-immersed air-cooled

- a) Oil-immersed, self-cooled: class ONAN
- b) Oil-immersed, self-cooled/forced-air-cooled: class ONAN/ONAF
- c) Oil-immersed, self-cooled/forced-air-cooled/forced-air-cooled: class ONAN/ONAF/ONAF

6.6.1.2 Oil-immersed air-cooled/forced-oil-cooled

- a) Oil-immersed, self-cooled/forced-air-cooled/forced-oil-cooled: class ONAN/ONAF/OFAF and class ONAN/ONAF/ODAF.
- b) Oil-immersed, self-cooled/forced-air forced-oil-cooled/forced-air forced-oil-cooled: class ONAN/OFAF/OFAF and class ONAN/ODAF/ODAF.

6.6.1.3 Oil-immersed water-cooled

- a) Oil-immersed, water-cooled: class OFWF and class ODWF.
- b) Oil-immersed, water-cooled/self-cooled; class OFWF/ONAN and class ODWF/ONAN.

6.6.1.4 Oil-immersed, forced-oil-cooled

- a) Oil-immersed, forced-oil-cooled with forced-air cooler; class OFAF and class ODAF.
- b) Oil-immersed, forced-oil-cooled, water-cooled; class OFWF and class ODWF.

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

Noise level limits, if required, shall be specified by the purchaser. Noise 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 noise 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.

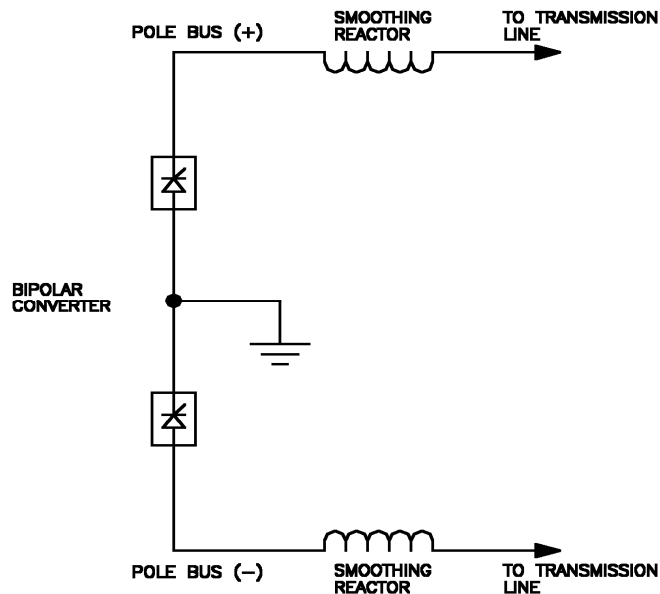


**Figure 1(a)—Smoothing reactor for HVDC transmission;
bipolar configuration**

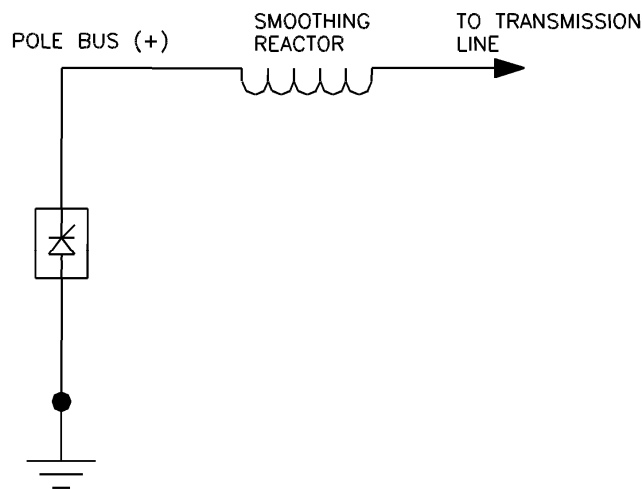
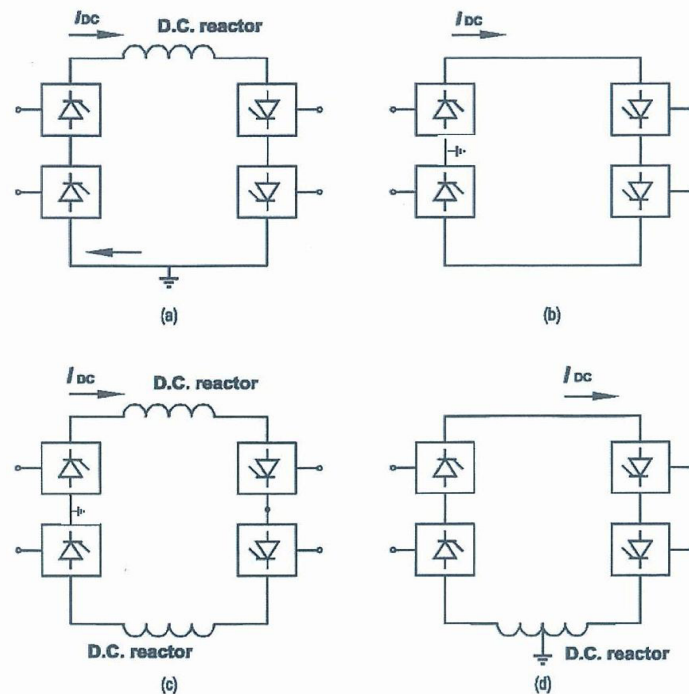


**Figure 1(b)—Smoothing reactor connections for HVDC transmission;
monopolar configuration**



- (a) Smoothing reactor connection at the dc pole with grounded dc neutral
- (b) Monopolar configuration without smoothing reactor with grounded midpoint
- (c) Smoothing reactor connections on positive and negative dc pole with grounded midpoint
- (d) Grounded tapped smoothing reactor connection at the dc neutral

**Figure 1(c)—Smoothing reactor connections for “back-to-back” converters:
sample configurations**

7. Construction of oil-immersed smoothing reactors

7.1 Tank and tank components for oil-immersed smoothing reactors

7.1.1 Tank pressure requirements

Tank pressure, under rated conditions, for smoothing reactors shall not exceed 203 kPa absolute pressure unless the requirements of applicable sections of the ANSI/ASME Boiler and Pressure Vessel Code (BPV), 1984 Edition, are met.

NOTE 1—203 kPa = 2 atmospheres.

Maximum operating pressures (positive and negative) for which the smoothing reactor is designed shall be indicated on the nameplate. The main tank, and any compartment attached thereto, that is subject to the operating pressures shall be designed to withstand, without permanent deformation, a pressure 25% greater than the maximum operating pressures, resulting from the system of oil preservation used.

NOTE 2—Individual designs may not necessarily reach the maximum pressures indicated in the definitions of oil-preservation systems.

Tanks for all smoothing reactors shall be designed to withstand vacuum filling (essentially full vacuum) in the field.

7.1.2 Cover construction

A bolted or welded main cover shall be provided. A bolted or welded bell-type tank can also be provided as an alternative to conventional tanks.

7.1.3 Core ground

A single core ground shall be provided and shall be accessible without removing oil. Cable or bus bar is utilized from ground pad to bushing.

7.1.4 Manholes

Manholes shall be provided in the cover. Manholes, if circular, shall have a minimum diameter of 460 mm. If rectangular or oval, they shall have minimum dimensions of 360 mm × 460 mm.

7.1.5 Drain and filter valves

A combination drain and lower filter valve of the ball or globe type shall be located on the side of the tank. This valve shall provide for drainage of the liquid to within 25 mm of the bottom of the tank. The drain valve shall have a built-in 10 mm sampling device, which shall be located in the inside of the valve between the main valve seat and the pipe plug. The device shall be supplied with a “5/16 in-32 male thread” for the user’s connection and shall be equipped with a cap.

The size of the drain valve for smoothing reactors is typically 25 mm or 50 mm, as appropriate or specified by the purchaser, and shall have National Pipe Thread (NPT) threads (in accordance with ANSI/ASME B1.20.1-1983) with nonferrous metallic pipe plug in open ends. Valves should not be located below any control cabinets.

If appropriate or specified by the purchaser, smoothing reactors shall have a 25 mm upper filter plug, or cap, located above the maximum liquid level.

In all other cases or as specified by the purchaser, smoothing reactors shall have an upper filter valve of the ball or globe type, located below the 25 °C liquid level. The size of the upper filter valve shall be 50 mm and it shall have “2-in NPT threads” (in accordance with ANSI/ASME B1.20.1-1983) with nonferrous metallic pipe plug in open ends.

7.1.6 Lifting, moving, and jacking facilities

7.1.6.1 Lifting facilities

Lugs for lifting the complete smoothing reactor shall be provided. The bearing surfaces of the lifting lugs shall be free from sharp edges and each lifting lug shall be provided with a hole having a minimum

diameter of 21 mm for guying purposes. Lifting eyes shall be provided for lifting the cover only. Adequate facilities shall be provided for lifting the core and coil assembly from the tank.

7.1.6.2 Moving facilities

The base of the smoothing reactor shall be designed to permit rolling or sliding in the direction of center lines and provision shall be made for pulling the smoothing reactor in these directions. The base shall be so designed that the center of gravity of the smoothing reactor, as normally prepared for shipment, should not fall outside the base support members for a tilt of the base of 15° from the horizontal, with or without oil in the smoothing reactor.

7.1.6.3 Jacking facilities

Jacking facilities shall be located near the corners of the tank.

Dimensions and clearances for jacking provisions shall be as shown in Figure 2.

7.1.7 Ground pads

Tank grounding provisions shall consist of two copper-faced steel pads or two stainless steel pads without copper facing, each 50 mm × 90 mm with two holes horizontally spaced on 44.5 mm centers and drilled and tapped for “1/2 in National Coarse Thread” (UNC) (as defined in ANSI/ASME B1.1-1989). The minimum thickness of copper facing (if used) shall be 0.4 mm.

Thread protection for the ground pad shall be provided.

Ground pads shall be welded on the base or on the tank wall near the base, and shall be located diagonally opposite from each other so as not to interfere with the jacking facilities.

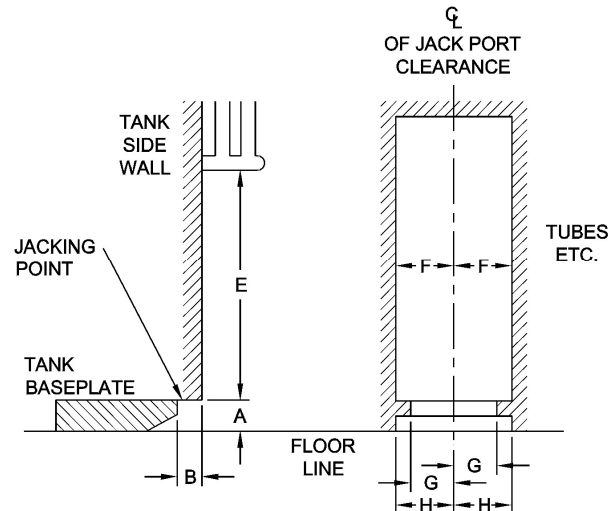
7.2 Oil preservation for oil-immersed smoothing reactors

7.2.1 Insulating liquids

Smoothing reactors shall be filled with a suitable insulating liquid such as mineral oil. New, unused mineral oil shall meet the requirements of ASTM D3487-1981. The appropriate quality of the oil, particularly resistivity and particle count that are required for initial commissioning and continued safety of operation, should be specified by the manufacturer. IEEE Std C57.106-2006 provides information concerning the acceptance and maintenance of mineral oil, including dielectric test breakdown criteria according to oil application, age, and test method.

NOTE 1—CIGRÉ JWG A2/B4.28 HVDC Converter Transformers has been established to assess the impact of oil conductivity. CIGRÉ JWG A2/D1 is specifically addressing testing of oil conductivity. Reports were not published at the time of this revision.

NOTE 2—IEC recommends that oil conductivity testing be carried out at a stress of 0.5 kV/mm. Oil conductivity testing is per IEC 61620:1998 [B13] and IEC 60247:2004 [B11]. The conductivity test is an ac test and test values may not be directly applicable for HVDC applications, but could be a useful relative reference.



Weight 15 900 kg or less (mm)	Weight 15 900 kg to 29 500 kg (mm)	Weight over 29 500 kg (mm)
A 89	A 127	A 457
B 64	B 64	B 102
E 686	E 686	E 508
F 127	F 127	F 127
G 76	G 76	G 76
H 127	H 127	H 127

NOTE 1—Dimensions E, F, G, and H are free clearances.

NOTE 2—Where required in the manufacturer's standards designs, any dimensions may be in excess of those shown.

NOTE 3—E applies to non-removable coolers only.

NOTE 4—Weight includes completely assembled reactor and fluid.

Figure 2—Jacking provisions

7.2.2 Insulating liquid preservation

Smoothing reactors shall be equipped with an insulating liquid preservation system such as sealed-tank, gas-oil seal, conservator, or conservator with diaphragm.

NOTE—The various insulating liquid (oil) preservation systems are described and defined in IEEE Std C57.12.80-2002.

7.3 Auxiliary equipment for oil-immersed smoothing reactors

7.3.1 Bushings

Smoothing reactors shall be equipped with bushings with an insulation level not less than that of the winding terminal to which they are connected, unless otherwise specified.

Bushings for use on oil-immersed smoothing reactors for HVDC application shall comply with IEEE Std C57.19.03-1996.

Bushings for use in smoothing reactors shall have impulse and low-frequency insulation levels as listed in IEEE Std C57.19.03-1996.

Smoothing reactors use specially designed dc bushings with design specific dimensions.

7.3.2 Bushing current transducers

7.3.2.1 Special bushing-type dc current transducers

Special bushing-type dc current transducers, or provision for their addition in the future, shall be as specified. They are special devices not covered by standards.

7.3.2.2 Bushing-type current transducer dimensions

Bushing-type current transducers used with bushings having dimensions in accordance with IEEE Std C57.19.03-1996 shall have an inside diameter adequate to accommodate the maximum D dimensions for those bushings, as shown in the applicable tables in the dc bushing standard.

7.3.2.3 Output leads

All bushing current transducer output leads shall be brought to an outlet box.

7.3.2.4 Terminal blocks

Nonsplit terminal blocks shall be provided in a weather-resistant case of the nonsplit type located near the smoothing reactor base for terminating alarm circuits specified in 7.3.4.

7.3.2.5 Bushing-type current transducer removal

Provisions shall be made for removing bushing-type current transducers from the tank without removing the entire tank cover of the smoothing reactor in which they are to be used.

7.3.3 Surge arresters

The following types of construction are available for surge protection:

- a) Provision only for the mounting of surge arresters.
- b) Mounting complete with surge arresters.
- c) Surge arrester ground pad consisting of a tank-grounding pad (in accordance with 7.1.7) mounted near the top of the tank may be specified for each set of arresters except that where the separation of the arrester stack is such that individual pads for grounding each phase arrester represent better design, individual ground pads may be supplied.
- d) Many utilities prefer to run copper cable from the ground grid directly to the arrester. In such cases provision to support the cable should be provided.

NOTE—Material for connecting surge arresters to live parts and to ground pads is not included.

7.3.4 Accessories

7.3.4.1 Liquid-level indicator

A liquid-level indicator shall be mounted so as to be readable at the level of the base. Dial markings shall show 25 °C level and the minimum and maximum levels. The words *liquid level* shall be shown on the face of the dial or on a suitable nameplate adjacent to the indicator.

7.3.4.2 Liquid-temperature indicator

A dial-type thermometer or thermocouple-based device shall be mounted on the side of the tank.

The temperature indicator shall have re-settable maximum temperature limits with corresponding contacts.

The thermometer shall be either a direct-stem mounted unit or a temperature sensing unit for remote eye-level indication. Either unit shall be mounted in a closed well located at a suitable level to indicate the top-oil temperature. For the dimensions of the well, see Figure 3.

The dial markings shall cover a minimum range of 0 °C to 120 °C. The words *liquid temperature* shall be shown on the dial or on a suitable nameplate mounted adjacent to the indicator.

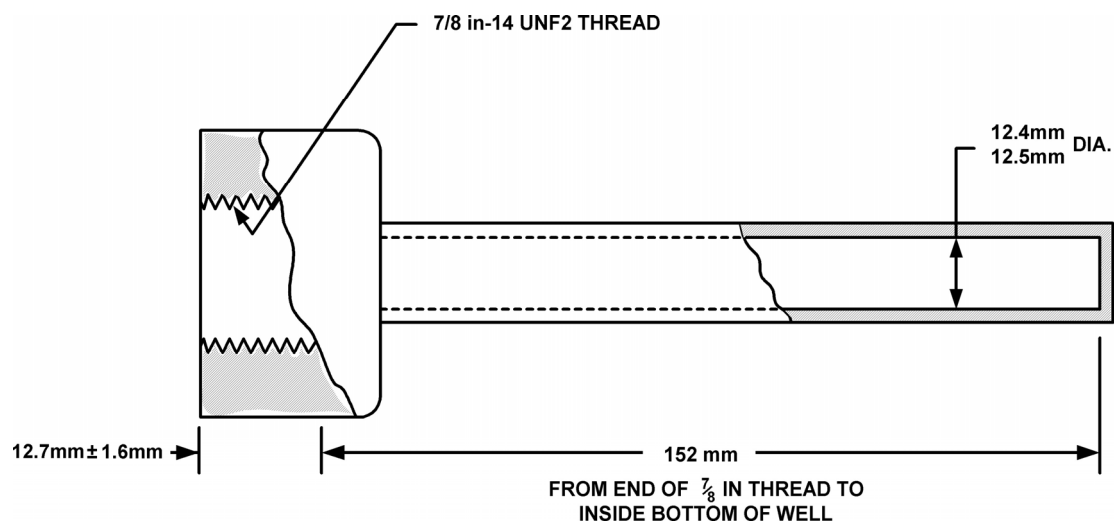


Figure 3—Dimensions of thermometer well

7.3.4.3 Temperature and liquid-level indicator alarm contacts

7.3.4.3.1 Alarm contacts

Nongrounded alarm contacts for liquid-level indicators and temperature indicators shall be dry, form-C type and shall be suitable for interrupting the following:

- a) 0.02 A dc inductive load
- b) 0.20 A dc noninductive load
- c) 2.5 A ac noninductive or inductive load
- d) 250 V maximum in all cases

The liquid-level indicator alarm contacts shall be nonadjustable and shall be set to close at the minimum safe operating level of the liquid.

The liquid temperature indicator alarm contacts shall be adjustable over a range of 65 °C to 110 °C.

The winding-temperature indicator alarm contacts shall be adjustable over a range of 95 °C to 125 °C.

7.3.4.4 Pressure-vacuum gauge

A pressure-vacuum gauge shall be provided for smoothing reactors of the sealed-tank and gas-oil-sealed construction.

7.3.4.5 Pressure-relief device

A pressure-relief device shall be provided on the smoothing reactor cover.

7.3.5 Controls power supply

7.3.5.1 Power-supply voltage

The power-supply voltage for the smoothing reactor controls shall be specified by the purchaser.

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 for smoothing reactors

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.

8.2.1 Types of tests

8.2.2 Routine tests

Routine tests shall be made on all smoothing reactors of a multiple-unit order in accordance with the requirements of Table 1 and Table 2, as applicable.

8.2.3 Design tests

Design tests, unless otherwise agreed between the purchaser and the manufacturer, shall be made on one smoothing reactor (of a specific design) of a multiple-unit order, in accordance with the requirements of Table 1 and Table 2, as applicable. Test reports documenting the results of a previous test on a smoothing reactor of a demonstrated similar design may be submitted for consideration by the purchaser in lieu of performing a design test.

8.2.4 Other tests

Other tests as shown in Table 1 and Table 2, 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 smoothing reactor of a demonstrated similar design may be submitted for consideration by the purchaser in lieu of performing an *other* design test.

8.2.5 Test sequence

8.2.5.1 General

The listing of tests shown in Table 1 and Table 2 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 oil-immersed and dry-type smoothing reactors, the losses measurement and temperature-rise tests shall be performed before all routine dielectric tests.

8.2.5.2 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-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. In addition, any of the other