IEEE Std 1277-2000

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

Sponsor

IEEE Transformers Committee
of the
IEEE Power Engineering Society

Approved 30 March 2000

IEEE-SA Standards Board

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

---

The Institute of Electrical and Electronics Engineers, Inc.
3 Park Avenue, New York, NY 10016-5997, USA

Published 5 June 2000. Printed in the United States of America.

Print: ISBN 0-7381-2478-8 SH94848
PDF: ISBN 0-7381-2479-6 SS94848

IEEE Standards documents are developed within the IEEE Societies and the Standards Coordinating Committees of the IEEE Standards Association (IEEE-SA) Standards Board. Members of the committees serve voluntarily and without compensation. They are not necessarily members of the Institute. The standards developed within IEEE represent a consensus of the broad expertise on the subject within the Institute as well as those activities outside of IEEE that have expressed an interest in participating in the development of the standard.

Use of an IEEE Standard is wholly voluntary. The existence of an IEEE Standard does not imply that there are no other ways to produce, test, measure, purchase, market, or provide other goods and services related to the scope of the IEEE Standard. Furthermore, the viewpoint expressed at the time a standard is approved and issued is subject to change brought about through developments in the state of the art and comments received from users of the standard. Every IEEE Standard is subjected to review at least every five years for revision or reaffirmation. When a document is more than five years old and has not been reaffirmed, it is reasonable to conclude that its contents, although still of some value, do not wholly reflect the present state of the art. Users are cautioned to check to determine that they have the latest edition of any IEEE Standard.

Comments for revision of IEEE Standards are welcome from any interested party, regardless of membership affiliation with IEEE. Suggestions for changes in documents should be in the form of a proposed change of text, together with appropriate supporting comments.

Interpretations: Occasionally questions may arise regarding the meaning of portions of standards as they relate to specific applications. When the need for interpretations is brought to the attention of IEEE, the Institute will initiate action to prepare appropriate responses. Since IEEE Standards represent a consensus of all concerned interests, it is important to ensure that any interpretation has also received the concurrence of a balance of interests. For this reason, IEEE and the members of its societies and Standards Coordinating Committees are not able to provide an instant response to interpretation requests except in those cases where the matter has previously received formal consideration.

Comments on standards and requests for interpretations should be addressed to:

Secretary, IEEE-SA Standards Board
445 Hoes Lane
P.O. Box 1331
Piscataway, NJ 08855-1331
USA

Note: Attention is called to the possibility that implementation of this standard may require use of subject matter covered by patent rights. By publication of this standard, no position is taken with respect to the existence or validity of any patent rights in connection therewith. The IEEE shall not be responsible for identifying patents for which a license may be required by an IEEE standard or for conducting inquiries into the legal validity or scope of those patents that are brought to its attention.

IEEE is the sole entity that may authorize the use of certification marks, trademarks, or other designations to indicate compliance with the materials set forth herein.

Authorization to photocopy portions of any individual standard for internal or personal use is granted by the Institute of Electrical and Electronics Engineers, Inc., provided that the appropriate fee is paid to Copyright Clearance Center. To arrange for payment of licensing fee, please contact Copyright Clearance Center, Customer Service, 222 Rosewood Drive, Danvers, MA 01923 USA; (978) 750-8400. Permission to photocopy portions of any individual standard for educational classroom use can also be obtained through the Copyright Clearance Center.

Introduction

(This introduction is not part of IEEE Std 1277-2000, IEEE Trial-Use 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 this standard there were only a limited number of papers, guides, and standards available that presented suggested dielectric tests for the HVDC equipment (see Annex D of this standard for a list of some of the most relevant documents). The IEC reactor standard IEC 60289:1988 also covers smoothing reactors in Clause 8; focus is not, however, application-specific. Clearly, 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 have been developed—one for oil-filled converter transformers and one for both dry-type and oil-filled smoothing reactors.

Significant accomplishments of this standard include:

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 has been included for oil-filled smoothing reactors to demonstrate insulation integrity for service conditions.

a) A consistent test methodology has been 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.

Publication of this trial-use standard for comment and criticism has been approved by the Institute of Electrical and Electronics Engineers. Trial-use standards are effective for 24 months from the date of publication. Comments for revision will be accepted for 18 months after publication. Suggestions for revision should be directed to the Secretary, IEEE-SA Standards Board, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, and should be received no later than 5 December 2001. It is expected that following the 24-month period, this trial-use standard, revised as necessary, shall be submitted to the IEEE-SA Standards Board for approval as a full-use standard.

This standard was produced by members of the HVDC Converter Transformers and Smoothing Reactors Subcommittee (Richard F. Dudley, Co-Chair and William (Bill) N. Kennedy, Co-Chair) and members of the Dry Type Reactor working group (Richard F. Dudley, Chair).

Richard F. Dudley, *Chair*

Dennis J. Allan
Raymond Allustiarti
Gene Blackburn
Dan DeLa Cruz
V. Dahinden
Fred Elliott
J. Foldi
J. Alan C. Forrest
K. R. Highton
Anthony J. Jonnatti
Lars-Erik Juhlin
Sheldon F. Kennedy
Frank A. Lewis
Nigel P. McQuin
Wesley F. Patterson
Klaus Papp
Paulette Payne
Carlos Piexoto
Greg S. Polovick
Einar Purra
Pierre Riffon
Michael Sharp
Georges H. Vaillancourt
Joe Watson
Gene Wolf

Other individuals who contributed to the development of this standard are:

James Cross
Peter Iijima
Jack W. McGill
W. W. Stein

The following members of the balloting committee voted on this standard:

S. H. Aguirre
Ron L. Barker
Mike Barnes
A. Bartek
Martin Baur
Enrique Betancourt
Thomas E. Blackburn, III
Simon R. Chano
Richard F. Dudley
Fred E. Elliott
Keith Ellis
Richard D. Graham
N. Wayne Hansen
Philip J. Hopkinson
James D. Huddleston, III
John S. Hurst
Charles W. Johnson
Lars-Erik Juhlin
Sheldon P. Kennedy
Barin Kumar
Stephen R. Lambert
J. P. Lazar
William A. Maguire
Richard P. Marek
K.T. Massouda
John W. Matthews
Nigel P. McQuin
Joe Melanson
Klaus Papp
Dhiru S. Patel
Paulette A. Payne
Dan D. Perco
Mark D. Perkins
Linden W. Pierce
Paul Pillitteri
E. Purra
J. C. Riboud
Pierre Riffon
Subhas Sarkar
Devki Sharma
Hyeong Jin Sim
Chuck Simmons
Tarkeshwar Singh
Craig L. Stiegemeier
Ron W. Stoner
John Vandermaar
Robert A. Veitch
Joe D. Watson

When the IEEE-SA Standards Board approved this standard on 30 March 2000, it had the following membership:

Also included is the following nonvoting IEEE-SA Standards Board liaison:

Alan Cookson, *NIST Representative*
Donald R. Volzka, *TAB Representative*

Noelle D. Humenick
IEEE Standards Project Editor

Contents

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

1. Scope

This trial-use standard applies only to oil-immersed and dry-type 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. References

This trial-use standard shall be used in conjunction with the following standards. When the following standards are superseded by an approved revision, the revision shall apply.

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.

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

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.

---

[1] ANSI publications are available from the Sales Department, American National Standards Institute, 11 West 42nd Street, 13th Floor, New York, NY 10036, USA (http://www.ansi.org/).

ASTM D117-1987, Standard Methods of Testing and Specifications for Electrical Insulating Oils of Petroleum Origin.[2]

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

IEC 60076-3 (2000-03), Power transformers—Part 3: Insulation levels, dielectric tests, and external clearances in air.[3]

IEC 60270 (1981-01), Partial discharge measurements.

IEC/TR2 61245 (1993-10), Artificial pollution tests on high-voltage insulators to be used on dc systems.

IEEE Std 1-1986 (Reaff 1992), IEEE Standard General Principles for Temperature Limits in the Rating of Electric Equipment and for the Evaluation of Electrical Insulation.[4]

IEEE Std 4-1995, IEEE Standard Techniques for High Voltage Testing.

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

IEEE Std 315A-1986, (Reaff 1993), Supplement to IEEE Std 315-1975 (Reaff 1993), IEEE Graphic Symbols for Electrical and Electronic Diagrams.

IEEE Std 693-1997, IEEE Recommended Practices for Seismic Design of Substations.

IEEE Std C57.12.00-1993, IEEE Standard General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers.

IEEE Std C57.12.80-1978 (Reaff 1992), IEEE Standard Terminology for Power and Distribution Transformers.

IEEE Std C57.12.90-1999, IEEE Standard Test Code for Liquid-Immersed Distribution, Power, and Regulating Transformers.

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

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

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

IEEE Std C57.106-1991, IEEE Guide for Acceptance and Maintenance of Insulating Oil in Equipment.

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

---

[2] 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/).

[3] IEC publications are available from the Sales Department of the International Electrotechnical Commission, Case Postale 131, 3, rue de Varembé, CH-1211, Genève 20, Switzerland/Suisse (http://www.iec.ch/). IEC publications are also available in the United States from the Sales Department, American National Standards Institute, 11 West 42nd Street, 13th Floor, New York, NY 10036, USA.

[4] IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA (http://standards.ieee.org/).

NEMA 107-1987, Methods of Measurement of Radio Influence Voltage (RIV) of High Voltage Apparatus.[5]

NEHRP-1997, (National Earthquake Hazards Reduction Program), Recommended Provisions for Seismic Regulations for New Buildings, [Federal Emergency Management Agency (FEMA), 1997].[6]

3. Definitions

Standard transformer terminology available in IEEE Std C57.12.80-1978[7] shall apply. Other electrical terms are defined in The IEEE Standard Dictionary of Electrical and Electronics Terms [B9].

3.1 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

- 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.
- 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.

3.2 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 predefined 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.

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

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

3.5 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.

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

---

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

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

[7] Information on references can be found in Clause 2.

4. Letter symbols

A	altitude
A_o	standard reference altitude of 1000 m
$E_{\text{ACapplied}}$	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
$I\text{ac}_{\text{equiv.}}$	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_{fetor}	core losses
P_h	harmonic losses of oil-immersed 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 below.

5.1.2 Temperature

When air is the cooling medium, the temperature of the cooling air (see 3.6) 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 vs. ambient temperature performance is required without loss of life, this must be clearly defined in the specification.

NOTES

1—Smoothing reactors may be uniquely (custom) specified and designed for a specific location and set of operating conditions and therefore, loading vs. ambient temperature condition may be the norm. Establishing a current rating vs. ambient temperature, etc., involves a number of considerations such as the thermal capability of the insulation system vs. 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.

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.

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 C57.12.00-1993. 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.

NOTE—The subject of correction factors for voltage when equipment is applied at altitudes above 1000 m is being reviewed by the Dielectric Test Subcommittee of the IEEE Transformers Committee. The focus will be to modify Table 1 in IEEE Std C57.12.00-1993 to more accurately reflect the continuous change in dielectric strength of insulating components (that depend in whole or in part on air for insulation strength) vs. altitude above sea level. In the interim, guidance regarding the dielectric strength of equipment components depending in whole or in part on air for insulation strength (especially when operated above 1000 m) can be found in IEEE Std 4-1995.

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 described below.

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 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 must be included in the specification for the smoothing reactor.

5.2.4 Seismic condition

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 693-1997 and NEHRP-1997 or other equivalent international seismic standard must be indicated in the smoothing reactor specification.

5.2.5 Other unusual service conditions

In addition to the usual service conditions described above, 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 must be accurately defined so that proper external insulation (particularly bushings and support insulators) may be provided. Pollution includes automotive, acid rain, (conductivities on the order of 1000–3000 µS/cm vs. less than 100 µS/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 y) should be specified.

f) Maintenance restrictions should be specified; especially if time between maintenance is longer than 1 y 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) Unusually strong magnetic fields.

j) Unusually high nuclear radiation.

k) Unusual number of line faults (> 30 per year) or commutation failures (> 50 per year).

l) Unusual harmonic (ripple) current content.

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

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, pole-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 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.

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

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.

NOTE—A minimum inductance must 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 rated dc current.

6.4.2 Tolerances

The tolerances on inductance apply from zero to rated dc current. In the case of oil-immersed smoothing reactors, the degree of linearity should be defined from zero to rated dc current along with a minimum inductance value at rated short-circuit current. For dry-type air-core smoothing reactors, a single tolerance on inductance is all that is required to be specified.

6.5 Basic impulse insulation level (BIL)

6.5.1 Coordination of insulation levels

The specified 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. The CIGRE publication [B2][8] 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 D 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). A switching impulse insulation level shall be specified for each terminal to ground and across the winding. A different switching impulse insulation level can be specified across the winding than for each terminal to ground depending on system studies.

---

[8] The numbers in brackets correspond to those of the bibliography in Annex D.

Very often for HVDC systems, there is no fixed standard ratio between the switching impulse insulation level 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 switching impulse insulation level is very often the main insulation design criteria.

Insulation coordination practice must 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 C57.12.90-1999. 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 Liquid-immersed air-cooled

a) Liquid-immersed, self-cooled: class ONAN

b) Liquid-immersed, self-cooled/forced-air-cooled: class ONAN/ONAF

c) Liquid-immersed, self-cooled/forced-air-cooled/forced-air-cooled: class ONAN/ONAF/ONAF

6.6.1.2 Liquid-immersed air-cooled/forced-liquid-cooled

a) Liquid-immersed, self-cooled/forced-air-cooled/forced-liquid-cooled: class ONAN/ONAF/OFAF

b) Liquid-immersed, self-cooled/forced-air forced-liquid-cooled/forced-air forced-liquid-cooled: class ONAN/OFAF/OFAF

6.6.1.3 Liquid-immersed water-cooled

a) Liquid-immersed, water-cooled: class OFWF

b) Liquid-immersed, water-cooled/self-cooled; class OFWF/ONAN

6.6.1.4 Liquid-immersed, forced-liquid-cooled

a) Liquid-immersed, forced-liquid-cooled with forced-air cooler; class OFAF

b) Liquid-immersed, forced-liquid-cooled, water-cooled; class OFWF

6.6.2 Cooling classes of dry-type smoothing reactors

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

6.7 Other specification 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 noise level limits

Noise level limits, if required, must 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 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.

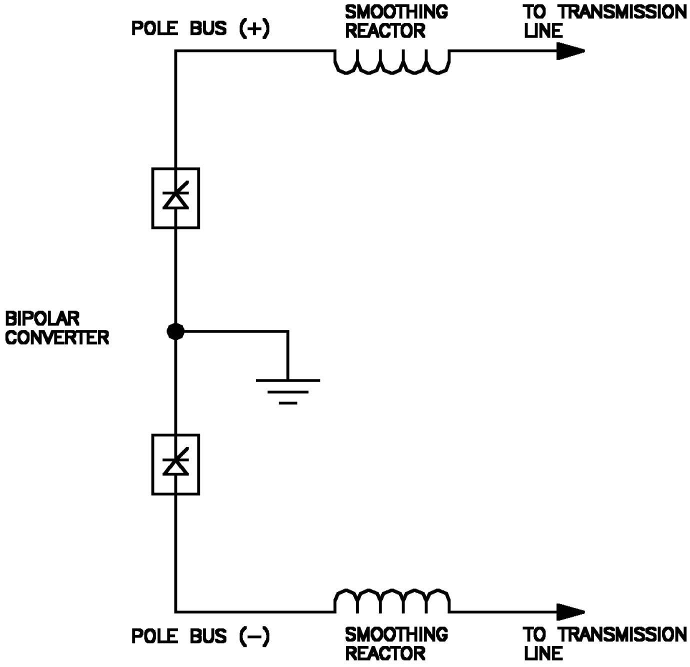


Figure 1a—Smoothing reactor connections HVDC transmission; bipolar configuration

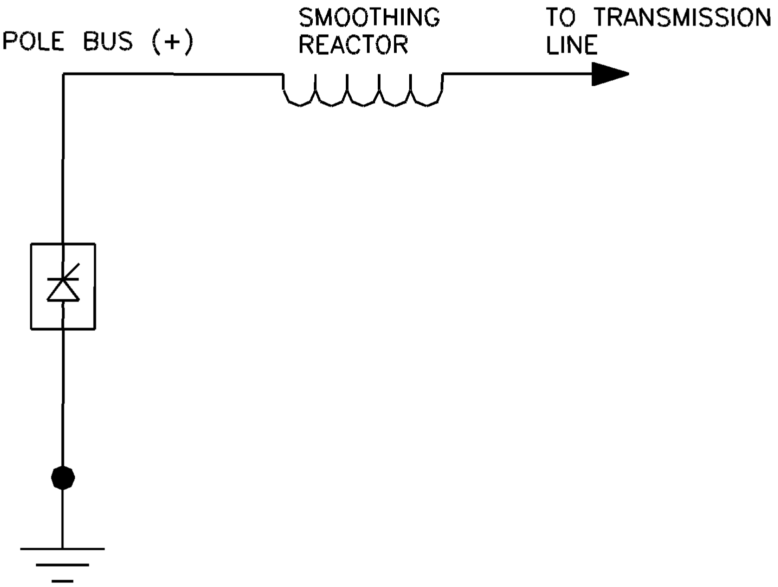


Figure 1b—Smoothing reactor connections HVDC transmission; monopolar configuration

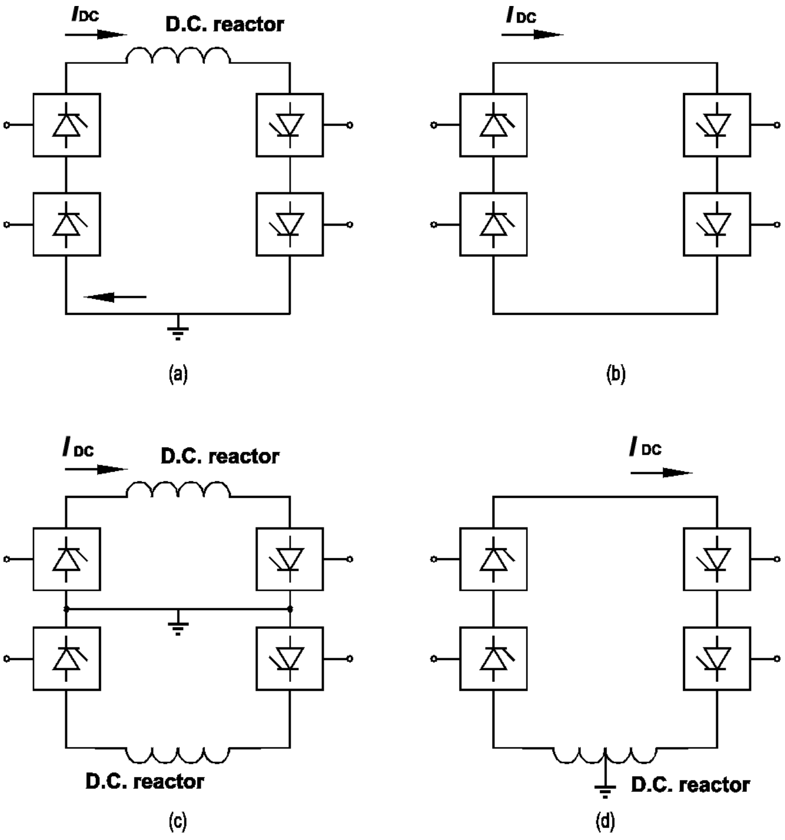


Figure 1c—Smoothing reactor connections back-to-back converter; sample configurations

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—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—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.

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 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 38 mm 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.

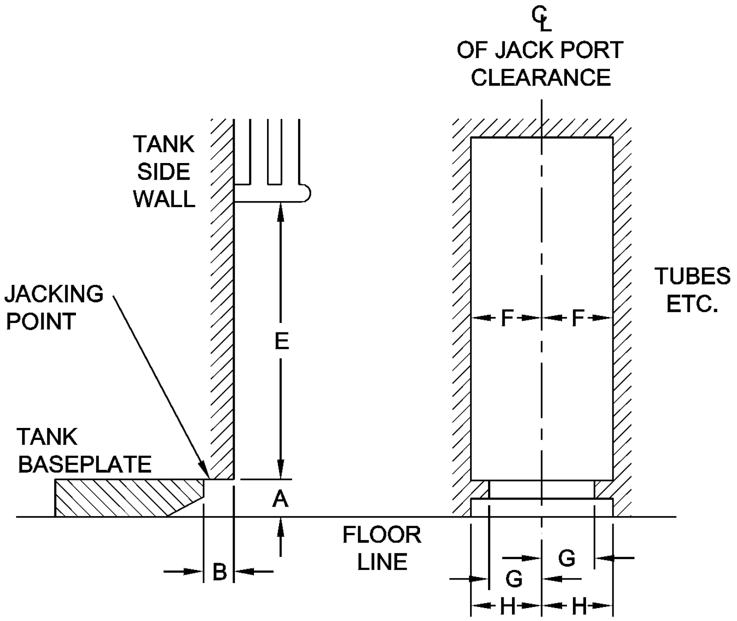
Ground pads shall be welded on the base or on the tank wall near the base, and shall be located diagonally opposite from each other so as not to interfere with the jacking facilities.

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 safe operation should be specified by the manufacturer.

NOTE—IEEE Std C57.106-1991 provides information concerning the acceptance and maintenance of mineral oil, including dielectric test breakdown criteria according to oil application, age, and test method.



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

NOTES:

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

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

3—E applies to nonremovable coolers only.

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 C57.12.80-1978.

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 loads

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 removed

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 must have resetable 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.

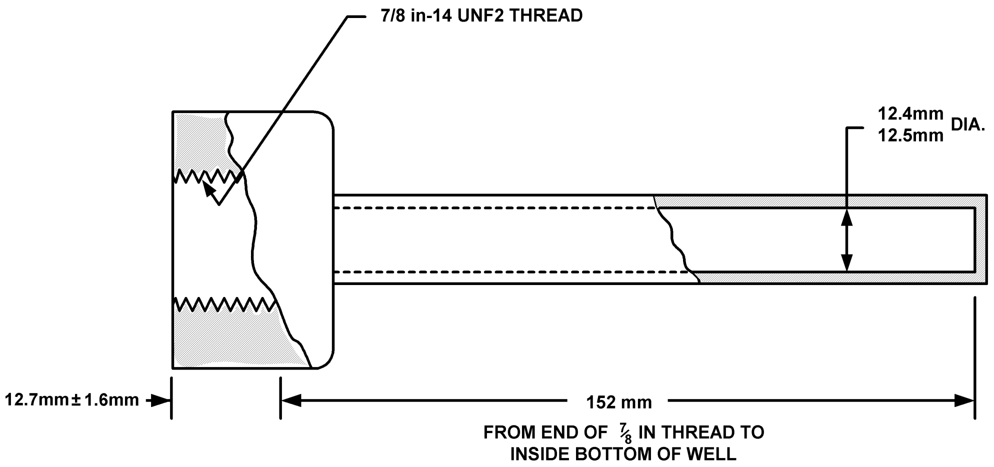


Figure 3—Dimensions of thermometer well

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:

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, respectively. 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 respectively, 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

The listing of tests shown in Table 1 and Table 2 does not necessarily indicate the sequence in which the tests shall be made. All tests are defined and shall be made in accordance with Clause 12.

8.2.6 Test sequence and other tests

If *other* tests are performed, their position in the sequence of tests should be determined by agreement between the purchaser and the manufacturer. In most cases, position in the test sequence is not critical and the test or verification can be performed or carried out as deemed appropriate, e.g., dc withstand voltage test (pollution), short-circuit capability verification, seismic, etc.

8.2.7 Test equipment and methods

Test equipment and methods (procedures) described in this document are state-of-the-art at the time of writing. Newer equipment and procedures that give equivalent or improved tests should be used, if available.

Table 1—Routine, design, and other tests for oil-immersed smoothing reactors

Tests	Routine	Design	Other
DC resistance	o		
Incremental inductance measurement	o (Note 4)		
Measurement of high-frequency impedance		o	
Loss measurement (dc and harmonics as applicable)	o		
Temperature-rise test		o (Note 5)	
DC power test			o (Note 6)
Dielectric tests			
Impulse tests			
Full wave impulse	o		
Chopped wave impulse			o
Switching impulse	o (Note 9)		
DC applied voltage (with partial discharge measurement)	o		
Polarity reversal (with partial discharge measurement)	o		
AC applied voltage (with partial discharge measurement)	o		
AC power test (with q-factor measurement)	o		
Insulation power factor	o (Note 1)		
Insulation resistance	o (Note 1)		
Audible sound level			o (Note 2)
Short-circuit verification			o (Note 3)
Capacitor discharge test			o (Note 7)
Pressure leak test	o		
Seismic verification			o (Note 8)

NOTES:

1—This test may not produce meaningful results if the smoothing reactor does not include an inner ground shield or core.

2—Suitable allowance must be made and mutually agreed upon for the harmonic contribution in service. Noise contributing elements of the reactor such as pumps and fans shall be operated as appropriate.

3—Calculations may be used based on a previous test of a reactor or model and strength of materials data in lieu of the short-circuit withstand test.

4—The incremental inductance shall be measured from zero current to the maximum temporary dc overcurrent (including the peak value of the rms sum of the harmonic currents).

5—The temperature-rise test may not be performed if the manufacturer demonstrates to the purchaser that temperature-rise test results on an equivalent unit are available.

6—The dc power test is a quality assurance test; the purpose of which is to detect broken conductors or bad connections. This test can be made part of the oil-particle filtration that is normally done prior to performing dielectric tests. The oil filtration is carried out by applying a dc current for several hours to the smoothing reactor. However, it is recommended that the issue be dealt with by resistance or continuity checks during manufacturing; and that such tests be part of an inspection and test plan and the manufacturer should not rely solely on a final test program.

7—This *other* test, when required, should be carried out at a frequency on the order of 300–900 Hz. Its purpose is to simulate operating conditions as described in Annex A. This test demonstrates voltage withstand capability.

8—Seismic qualification may be done by analytical methods. Refer to IEEE Std 693-1996.

9—The switching impulse test across the windings of an oil-immersed smoothing reactor is a routine test. In general, it is difficult to obtain the required waveshape due to the kilojoule limitations of existing impulse generators. The switching impulse test to ground is a routine test.

Table 2—Routine, design, and other tests for dry-type smoothing reactors

Tests	Routing	Design	Other
DC resistance	o (Note 1)		
Inductance	o (Note 1)		
Measurement of high frequency impedance		o	
Loss measurement (dc and harmonics as applicable)	o (Note 1)		
Temperature-rise test		o (Note 8)	
DC power test			o (Note 5)
Dielectric tests			
Impulse tests			
Full wave impulse	o (Note 10)		
Chopped wave impulse		o	
Switching impulse		o (Note 9)	o (Note 9)
AC power test	o		
DC wet voltage withstand test		o (Note 2)	
DC pollution test on insulators			o (Note 6)
RIV test			o
Audible sound level			o
Short-circuit verification			o (Note 3)
Capacitor discharge test			o (Note 7)
Seismic verification			o (Note 4)

NOTES:

1—The routine test sequence for dry-type air-core smoothing reactors consists of dc resistance, inductance, loss measurement, dielectric, dc resistance (repeated), inductance (repeated), and loss measurement (repeated). For the order of dielectric tests refer to 12.6.2.

2—This test may be waived for smoothing reactors installed in the neutral bus, depending on system design requirements, or if the smoothing reactor is to be installed indoors.

3—Calculations may be used, based on a previous test of a reactor or model and strength of materials data in lieu of the short-circuit withstand test.

4—Seismic qualification may be done by analytical methods. Refer to IEEE Std 693-1996.

5—The dc power test is a quality assurance test, the purpose of which is to detect broken conductors or bad connections.

6—This *other* test, when required, is to demonstrate performance of the support insulators only, under conditions of pollution. It is a wet dc withstand test with contamination levels as specified by the purchaser. It is a test to be carried out on at least one of the support insulators.

7—This *other* test, when required, should be carried out at a frequency on the order of 300–900 Hz. Its purpose is to simulate operating conditions as described in Annex A. This test demonstrates voltage withstand capability.

8—The temperature-rise test may not be performed if the manufacturer demonstrates to the purchaser that temperature-rise test results on an equivalent unit are applicable.

9—The switching impulse test is a design test when performed across the support insulators to ground.It is an *other* test when performed across the winding of a dry-type air-core smoothing reactor since it is not possible to obtain the desired waveshape due to the kilojoule limitations of existing impulse generators.

10—If a dry-type air-core smoothing reactor is supplied with a pollution or sound mitigation shield (enclosure), the impulse-design test shall be carried out with the mitigation measures installed.

9. Losses and inductance

9.1 Losses

9.1.1 Total losses

The losses of a dc smoothing reactor are those losses that are incident to the carrying of a current. They include the following:

a) The resistance loss in the winding due to the dc load current constitute the primary loss in a dc smoothing reactor.

b) Harmonics or ripple currents produce both resistive and eddy-current losses in the winding. These losses are significantly smaller than the dc losses.

c) Losses caused by circulating currents in parallel windings.

d) Stray losses caused by magnetic flux in other metallic parts of the reactor are typically a very small percentage of total losses, due to the low magnitude of the ripple current.

e) For dry-type smoothing reactors losses include those occurring in the support structure. Due to the low magnitude of the ripple current, the stray losses in the support structure are usually a small percentage of total losses.

f) For oil-immersed smoothing reactors core losses are typically 1.0–1.5% of total losses. In a few rare cases, due to the magnitude of the harmonics, the core losses have been as high as 2% of total losses.

g) For oil-immersed smoothing reactors, power required for cooling fans, oil pumps, space heaters, and other ancillary equipment is not included in the total loss. When specified or requested by the purchaser, loss data on such ancillary equipment shall be furnished.

9.1.2 Tolerance on losses

A tolerance on losses is utilized for two purposes. One is for commercial evaluation and the other is to provide the basis of a quality check.

9.1.2.1 Tolerance on losses for commercial evaluation

As energy costs increase, losses become a more significant component of total operating costs and as such may be capitalized by the purchaser. Therefore, compliance to guaranteed losses becomes part of the commercial contract. A tolerance on losses, to account for measurement tolerances, etc., may be part of the contractual agreement. If the measured losses corrected to reference temperature exceed the guaranteed loss by more than 10% it may be indicative of a design issue.

Additionally, the contract may specify such guarantee criteria as maximum loss per unit, average loss for all units, total package losses, etc. In any case, this is purely a commercial matter between the purchaser and the manufacturer.

It should be stressed that if a unit exceeds guaranteed loss, aside from the commercial implications which are a matter between the manufacturer and the purchaser, it is essential to demonstrate that temperature-rise limits, for the insulation systems employed, are not exceeded.

9.1.2.2 Tolerance on losses as the basis of a quality check

The losses, as defined in the specification, on any reactor shall not differ from the average loss of all units of the same design by more than 6%. The average loss shall be calculated by using the measured losses on each individual unit.

If one of the units exceeds this tolerance, the manufacturer shall initiate an investigation in order to find the cause of this deviation. In order for acceptance to be considered, the manufacturer shall demonstrate to the purchaser, by either calculation and/or test, that the deviation will not impair the ability of the unit to meet the other requirements of this standard, particularly the temperature-rise limits.

9.2 Inductance

9.2.1 Tolerances on inductance

9.2.1.1 Tolerance and current

Tolerances on inductance apply over a current range from zero to full-rated current. The minimum inductance at short circuit must be specified.

9.2.1.2 Tolerance percentage

The inductance of a smoothing reactor shall have a standard tolerance of ±7% or, if specified, shall not vary from the specified value set by the purchaser by more than a specified plus or minus percent. The tolerance on inductance may impact the design of the dc filters.

10. Temperature rise and loading conditions

10.1 Temperature-rise limits and loading conductors

Temperature-rise limits for HVDC smoothing reactors are presented in Table 3.

Since smoothing reactors on HVDC schemes (transmission or back-to-back) are almost always loaded at or near nameplate rating, the maximum hottest-spot temperature-rise limits are selected to be conservative. The maximum hot-spot temperature-rise limits in Table 3 are based on continuous operation in a 30 °C daily average ambient with a 40 °C maximum.

If the actual annual ambient temperature is lower, or the smoothing reactor sees lower than nameplate loads for extended periods of time, then consideration can be given to increasing the allowable hottest-spot winding temperature-rise limits.

Conversely, many HVDC schemes have overload conditions specified as part of their standard operating mode (e.g., seasonal overloads, monopolar operation). HVDC smoothing reactors are directly impacted by such requirements and, hence, the maximum hottest-spot temperature rise should either reflect the worst-case service duty or the hottest-spot temperature rise at normal nameplate current rating should be adjusted accordingly.

Total hot-spot temperature defines the rate of aging of insulation and in conjunction with time at temperature determines service life. Therefore, care should be taken in selecting insulation materials and in selecting (design objectives) total operating hot-spot temperature for full load rated current, short-time overloads, and continuous overloads.

Table 3—Limits of temperature rise for HVDC smoothing reactors

Insulation temperature class	Average winding temperature rise by resistance (°C)	Hottest-spot winding temperature rise (°C)
Type of smoothing reactor		
Oil-immersed	65	80
Dry-type		
(A) 105	55	65
(B) 130	80	90
(F) 155	100	115
(H) 180	125	140
(C) 220	150	180

NOTES:

1—The insulation temperature classes in Table 3 are selected in accordance with the preferred temperature index for insulation materials as defined in ANSI/IEEE Std 1-1986.

2—The assignment of the reactors' insulation system to a certain temperature class shall be proven by experience or testing.

3—The average temperature rise and hot-spot temperature rise are upper limits and neither are to be exceeded.

4—The difference between the hot-spot rise and the average rise is not intended to be an indication of hot-spot allowance. Hot-spot allowance is very much design related and no simple rule can account for it, especially with the wide variety of custom designs available today.

10.2 Temperature of metalic parts in contact with insulation

Metallic parts in contact with or adjacent to the insulation system shall not attain a temperature in excess of that allowed for the hottest spot of the windings adjacent to that insulation.

10.3 Temperature of other metalic parts

Metallic parts other than those covered in 10.2 above shall not attain excessive temperature rises. In the case of oil-immersed smoothing reactors, this includes magnetic shields, tank walls, etc. Operating temperatures should be consistent with the capabilities of the oil/paper insulation system, typically 120 °C under normal operating conditions. In the case of dry-type air-core smoothing reactors, auxiliary metallic components include support structure elements such as insulator caps, spring/damping systems (for seismic application), insulator mounting brackets, bracing elements, etc. Allowable in-service operating temperatures should be consistent with the capabilities of the materials employed.

10.4 Temperature rise of insulating liquid

The temperature rise of the insulating liquid in an oil-immersed smoothing reactor should not exceed 65 °C rise when measured near the top of the tank.

10.5 Temperature rise of terminals

The temperature rise of terminals should be lower than 50 °C for bare aluminum or copper, 65 °C for tin-plated, and 75 °C for silver- or nickel-plated. Higher temperatures are allowable, depending on the use of various termination methodologies and contact aids.

11. Dielectric tests and insulation levels

11.1 Impulse tests

11.1.1 General

In order to ensure the best possible diagnostics, all design and routine impulse tests shall be carried out using a digital impulse test system—the transfer function calculation is one obvious benefit. Smoothing reactors for HVDC application are critical pieces of equipment and the best available test technology must be used.

11.1.2 Full-wave impulse tests

An impulse test level shall be specified for each terminal to ground and across the winding. If chopped-wave impulse tests are required, impulse tests shall include reduced full-wave, chopped-wave, and full-wave tests.

11.1.3 Switching impulse tests

When required, the winding shall be subjected to switching impulse tests to ground. These should be performed with both ends of the tested winding connected together. The test level to ground shall be specified by the purchaser. This is applicable to oil-immersed and dry-type smoothing reactors.

If a switching impulse withstand test is specified across the winding of an oil-immersed or dry-type smoothing reactor, a switching impulse test should be performed across the winding—from both terminals with the other terminal grounded. For low inductance smoothing reactors, the energy available from the impulse generator may not be sufficient to produce the required wave shape. In such cases, the manufacturer should advise the purchaser at the bid stage.

11.1.4 Chopped-wave test

In the case of oil-immersed or dry-type air-core smoothing reactors, the chopped-wave test, when required, is a test mainly of the winding turns insulation.

11.2 DC voltage tests

11.2.1 DC voltage tests with partial discharge measurements for oil-immersed smoothing reactors

These tests are carried out by applying a voltage of positive polarity to the terminals of the winding of the smoothing reactor for a duration of 2 h. The test voltage is given by

$$E_{\mathrm{dc}} = 1.5 \; E_{\mathrm{dcSystem}} \tag{1}$$

11.2.2 DC voltage tests for dry-type smoothing reactors

This test is applied to the insulators of the smoothing reactor. The dc test voltage applied for 1 h under wet conditions is given by

$$E_{\mathrm{dc}} = 1.5 \; E_{\mathrm{dcSystem}} \tag{2}$$

11.3 DC polarity-reversal test with partial discharge measurements for oil-immersed smoothing reactors

This test shall be applied to the terminals of the winding(s) connected together. The test level for smoothing reactors is

$$E_{PR} = 1.25\ E_{\mathrm{dcSystem}} \tag{3}$$

A double reversal test shall be used as shown in Figure 4. The duration of the first two voltages is 90 min each, while the duration of the last voltage is 45 min. The reversal should be accomplished within 2 min maximum.

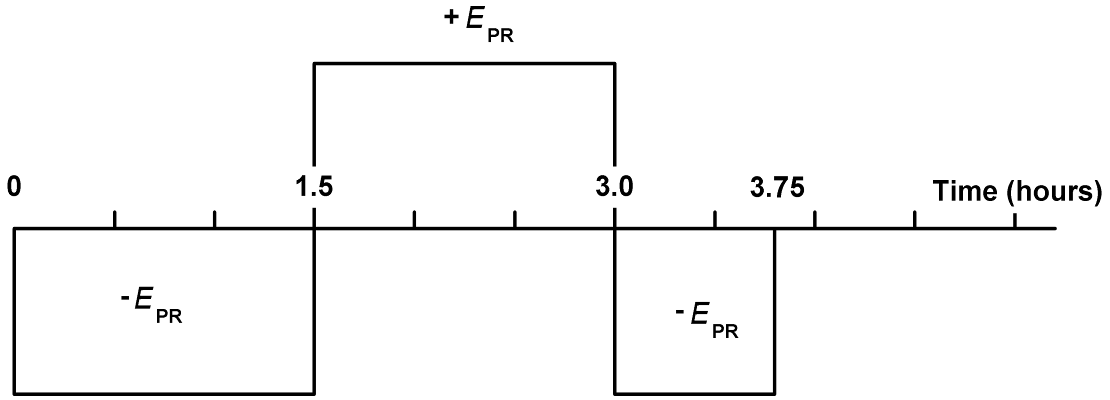


Figure 4—Double polarity reversal

11.4 Low-frequency voltage tests on line terminals

11.4.1 AC applied voltage test to ground with partial discharge measurements for oil-immersed smoothing reactors

For oil-immersed smoothing reactors, winding terminals shall receive an ac applied voltage test to ground. The rationale for this test can be found in the CIGRÉ paper [B14]. The duration of the test shall be 60 min, and the test level is given by

$$E_{\mathrm{acApplied}} = \frac{1.5E_{\mathrm{dcSystem}}}{\sqrt{2}} \tag{4}$$

11.4.1.1 AC power test between terminals with Q-factor measurements

This is an ac power test (across the winding) with Q-factor measurement. The purpose is to verify winding insulation integrity after all dielectric tests are completed.

NOTE—The Q-factor measurement is not for the purpose of loss guarantees. For loss-guarantee purposes the harmonic losses will be calculated.

The frequency of the power supply shall be between power frequency (60 Hz, or 50 Hz) and 1000 Hz. The test voltage shall be at 2 times the maximum specified continuous harmonic voltage drop. The duration of the test shall be 5 min. The Q-factor or losses at test supply frequency will be measured at the beginning of the dielectric test sequence and these values will be compared to those measured during the ac power test.

12. Test code

12.1 General

This clause prescribes methods for performing the tests specified in Clause 8. Although the figures of this standard show conventional meters, adequate digital readout measuring devices and digital sampling techniques with computer calculations are considered as satisfactory alternatives and may actually be preferred as mentioned in various places in the text.

12.2 Resistance measurements

Resistance measurements are of fundamental importance for the following purposes:

a) Calculation of I^2R component of conductor losses
b) Calculation of winding temperature at the end of a temperature test
c) As a basis for assessing possible damage in the field

12.2.1 Determination of cold temperature

The cold temperature of the winding shall be determined as accurately as possible when measuring the cold resistance. The following precautions should be observed.

12.2.1.1 General

The reactor shall be located in a room free of drafts, with a relatively constant temperature for a period of at least 5 times the thermal time constant before cold resistance readings are taken.

12.2.1.2 Oil-immersed smoothing reactors: windings immersed in insulating liquid

The temperature of the winding shall be assumed to be the same as the mean value of the top and bottom temperatures of the insulating liquid, provided

a) The winding has been under insulating liquid with no excitation and with no current in the winding for a time of 3 h to 8 h (depending on the size of the smoothing reactor) before the cold resistance is measured.
b) The temperature of the insulating liquid has stabilized, and the difference between the top and bottom temperatures does not exceed 5 °C.

12.2.1.3 Dry-type air-core smoothing reactors

The temperature of the windings shall be determined by placing thermometers, thermocouples, or thermal sensors along the length and around the circumference of the outermost winding group. The average of the recorded temperature shall be taken as the winding temperature. Good contact can be assured by using a material such as silicone to hold the end of the thermometer or thermocouple in place.

12.2.2 Conversion of cold resistance measurements

Cold winding resistance measurements are normally converted to a standard reference temperature equal to the rated average winding temperature rise plus 20 °C. In addition, it may be necessary to convert the resistance measurements to the temperature at which the impedance loss measurements were made. The conversions are accomplished by the following formula

$$R_s = R_m \frac{T_s + T_k}{T_m + T_k} \tag{5}$$

where

R_s is resistance at desired temperature, T_s,
R_m is measured resistance,
T_s is desired reference temperature,
T_m is temperature at which resistance was measured,
T_k = 234.5 °C for copper
= 225 °C for aluminum.

NOTE—The value of T_k may be as high as 230 for alloyed aluminum. In general, for any other type of conductor material the appropriate constant of T_k shall be used. In such cases, the manufacturer shall demonstrate by test or calculations, the validity of the constant T_k .

12.2.3 Methods for measuring resistance

Bridge or drop-of-potential (volt-ammeter) methods may be used for measuring dc resistance. If a voltmeter-ammeter method is employed, the test current should be such as to not produce a rise in temperature of the winding; less than 15% of rated current. Digital voltmeters and digital ammeters of appropriate accuracy are commonly used in connection with temperature-rise determinations.

12.2.3.1 Readings and calculation of resistance

Measurement is made with dc, and simultaneous readings of current and voltage are taken using the connections of Figure 5. The required resistance is calculated from the readings in accordance with Ohm's Law. A battery or filtered rectifier will generally be more satisfactory as a dc source than a commutating dc machine. The latter may cause the voltmeter pointer to vibrate because of voltage ripple.

12.2.3.2 Errors of observation

To minimize errors of observation

a) The measuring instruments shall have such ranges as will give reasonably large deflection.
b) For all iron-core oil-immersed smoothing reactors, the polarity of the core magnetization shall be kept constant during all resistance readings.

NOTE—A reversal in magnetization of the core can change the time constant and result in erroneous readings.

12.2.3.3 Voltmeter leads

The voltmeter leads shall be independent of the current leads and shall be connected as closely as possible to the terminals of the winding to be measured. This is to avoid including in the readings the resistances of current-carrying leads and their contacts and of extra lengths of leads (Figure 5).

To protect the voltmeter from injury by off-scale deflections, the voltmeter should be disconnected from the circuit or shunted by a bypass switch before switching the current off.

12.2.3.4 Steady-state conditions

Readings shall not be taken until after the current and voltage have reached steady-state values.

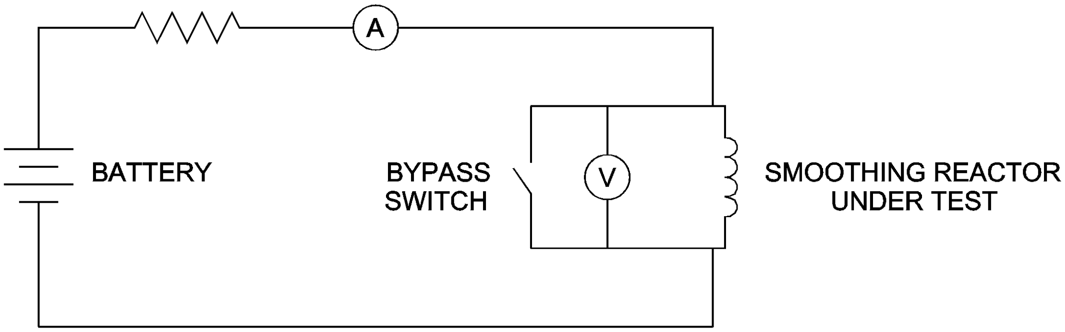


Figure 5—Connections for the voltmeter-ammeter method of resistance measurement

When measuring the cold resistance, prior to making a temperature-rise test, note the time required for the readings to become constant. The period thereby determined should be allowed to elapse before taking the first reading when the final winding hot resistance measurements are being made.

In general, the winding will exhibit a long dc time constant. To reduce the time required for the current to reach its steady-state value, a noninductive external resistor should be added in series with the dc source. The resistance should be large compared to the inductance of the winding. It will then be necessary to increase the source voltage to compensate for the voltage drop in the series resistor.

12.2.3.5 Readings and values of current

Readings shall be taken with not less than four values of current. The average of the resistances calculated from these measurements shall be considered to be the resistance of the winding.

The current used shall not exceed 15% of the rated current of the winding whose resistance is to be measured. Larger values may cause inaccuracy by heating the winding and thereby changing its temperature and resistance.

12.3 Losses and impedance

12.3.1 Impedance test

The impedance voltage comprises an effective resistance component corresponding to the impedance losses, and a reactance component corresponding to the flux linkages of the winding.

12.3.2 Measurement of incremental inductance for oil-immersed smoothing reactors

Due to iron-saturation effects, the inductance of oil-immersed smoothing reactors is not linear. Therefore, the incremental inductance shall be determined as a function of the dc from zero up to the specified maximum overload current plus the peak value of the rms sum of the harmonic currents.

The test shall be performed by registering the current decay in the short-circuited smoothing reactor. The reactor shall be *charged up* with a current from a rectifier to a value of current equal to the maximum overload current or higher, if necessary, to ensure the core material saturation characteristic beyond the *knee point* is accounted for. This will ensure that the inductance at any current value, including short circuit, can be determined. The reactor is then short-circuited through a current shunt and the rectified voltage source is disconnected.

The current decay through the reactor is registered in sufficient detail for several seconds, in order to provide adequate information from which the curve of incremental inductance vs. dc can be derived. At every instant the following relation holds true

$$-L(di/dt) = Ri \tag{6}$$

where

R is the resistance of the discharge circuit (reactor, connecting leads, and measurement shunt).

The circuit resistance shall be kept as low as possible and should be measured before and after the test in order to take into account the effect of temperature rise on the discharge circuit components. The mean value of the resistance measured before and after the test shall be used as the circuit-resistance value. The slope of the current curve at every point represents the inverse value of the incremental inductance.

The incremental inductance at dc currents close to zero may be determined accurately with ac excitation at relatively low voltage.

12.3.3 Measurement of inductance of dry-type smoothing reactors

The inductance shall be measured at 50 or 60 Hz at any convenient current provided the measurement is disturbance free. The test shall be repeated after the dielectric test. The values should be consistent within measurement accuracy and repeatability.

12.3.4 Measurement of harmonic impedance of dry-type smoothing reactors

It may be required that the impedance and especially the Q-factor of a dry-type SMR be measured at the 12^{th} and/or the 24^{th} harmonics. The measurements can provide information for evaluation of the total losses and may be required for systems modeling.

12.3.5 Losses

12.3.5.1 Measurement of losses of dry-type air-core smoothing reactors

12.3.5.1.1 Total losses of dry-type smoothing reactors

For dry-type HVDC smoothing reactors, the total losses shall be calculated at reference temperature as the sum of the losses at rated dc current and losses at all harmonic currents defined in the harmonic current spectrum for rated operating conditions.

12.3.5.1.2 Measurement methodology for dry-type air-core smoothing reactors

The impedance of a dry-type air-core smoothing reactor remains constant with current and therefore losses may be measured at any value of current and corrected to rated harmonic current. (For temperature correction of the impedance loss, refer to 12.3.7.)

$$P_r = \left(\frac{I_r}{I_m}\right)^2 P_s \tag{7}$$

where

P_r is losses at rated current,
I_r is rated current,
I_m is current in the reactor when losses were measured,
P_s is losses at reference temperature, T_s, and measured current, I_m.

12.3.5.1.3 Bridge methods

Bridge methods allow the simultaneous measurement of reactance (inductance) and effective resistance. The impedance is calculated by the following equation:

$$Z_h = \sqrt{R_h^2 + X_h^2} \tag{8}$$

where

Z_h is impedance at harmonic frequency,
R_h is resistance component of the impedance at harmonic frequency,
X_h is reactance component of the impedance at harmonic frequency.

If a wattmeter is used to determine losses, then impedance can be calculated by measuring simultaneous current and voltage and dividing the voltage by the current.

Resistance and reactance components of the impedance voltage are determined

$$E_r = \frac{P_a}{I} \tag{9}$$

$$E_x = \sqrt{(E_Z^2 - E_r^2)} \tag{10}$$

where

E_r is resistance voltage component, in-phase component,
P_a is watts measured in impedance test of winding carrying current,
I is current in winding on which voltage is impressed (A),
E_x is reactance voltage component, quadrature component,
E_z is impedance voltage of winding carrying current.

12.3.5.1.4 Q-factor at main ripple harmonic frequencies

When requested by the purchaser, the Q-factor at the major ripple harmonic frequencies should be measured and reported.

12.3.5.2 Measurement of total losses of oil-immersed smoothing reactors

For oil-immersed smoothing reactors, the losses consist of four components

a) $I_{dc}^2 R_{dc}$ losses in windings and leads
b) Eddy losses and resistive losses in windings due to harmonic currents

c) Stray losses in enclosure or tank due to harmonic currents

d) Core losses

The total harmonic losses are the sum of the losses as described in items b)–d). The individual harmonic loss components described in items b)–d) cannot be separated by measurement. Therefore, a value for the core losses provided by the manufacturer should be used in the loss calculations for oil-immersed smoothing reactors as presented in 12.3.8.

NOTE—For a typical oil-immersed smoothing reactor, the $I_{dc}^2R_{dc}$ losses represent approximately 95% of the total losses while the harmonic losses (including the core losses which account for about 50% of the harmonic losses) represent the remainder. Therefore, any resultant inaccuracy, due to using a core-loss figure that is not based on measurement, is low. For instance, an error of 20% in calculating core losses results only in an error of 0.5% for the total losses.

12.3.6 Conversion of dc losses to reference temperature

The losses at rated dc current are corrected to reference temperature by converting the dc resistance to the reference temperature using Equation (5) and then calculating the I^2R loss using the rated dc current.

12.3.7 Conversion of resistance and stray losses to reference temperature

The I^2R component of the impedance loss at any harmonic frequency increases with the temperature while the stray-loss component diminishes with temperature. Consequently, when it is desired to convert the impedance losses from one temperature to another, the two components of the impedance loss are converted separately. Thus

$$P_r = P_{rm}\frac{T_k + \theta}{T_k + \theta'} \quad (11a)$$

where

$$P_S = P_{sm}\frac{T_k + \theta'}{T_k + \theta} \quad (11b)$$

T_k = 234.5 °C for copper,
= 225 °C for aluminum.

P_r and P_s are the resistance and stray losses, respectively, at the specified temperature Θ °C and P_{rm} and P_{sm} are the measured resistance and stray losses at temperature Θ' °C.

12.3.8 Loss calculations for oil-immersed smoothing reactors

The procedure for determining losses of an oil-immersed smoothing reactor is as follows:

a) Measure all winding resistances

b) Calculate I_{dc}^2R loss (P_{dc}) using rated dc current and correct loss value to the standard reference temperature of 85 °C by using Equation (11a).

c) Measure harmonic losses for each specified harmonic current. Calculate the associated $I_h^2R_{dc}$ loss and stray losses. This measurement shall be carried out at zero dc current; harmonic current only. The value for the core loss provided by the manufacturer shall be deducted from this measurement. Correct the measured losses to the standard reference temperature of 85 °C by using Equation (11a) and Equation (11b).

d) Correct the measured harmonic losses at each harmonic frequency for the specified harmonic current amplitude (I_h) by using Equation (7).

e) The total losses at 85 °C is calculated

$$P_{LLT} = P_{\mathrm{dc}} + \Sigma P_h \tag{12}$$

where

P_{LLT} is total load losses at T = 85 °C,
P_h is harmonic losses (including core losses) at harmonic frequency, h, and corrected to 85 °C.

12.4 Temperature-rise test

12.4.1 Loading for temperature-rise test

The smoothing reactor shall be tested under loading conditions that will give losses equal to or higher than those obtained at rated current, including rated harmonic currents, in the winding. Since it is usually not possible to apply both dc current and harmonic current simultaneously, the test shall be made with dc current that produces losses in the reactor winding equivalent to the total losses calculated in Equation (7) in the case of dry-type air-core smoothing reactors and Equation (12) in the case of oil-immersed smoothing reactors.

The thermal equivalent dc current for the test shall be calculated

$$I_{\mathrm{test}} = \sqrt{(I_{dc}^2 R_{\mathrm{DC}} + P_{\mathrm{htot}}) / R_{\mathrm{DC}}} \tag{13}$$

where

I_{test} is dc test current,
I_{dc} is rated dc current,
P_{htot} is sum of harmonic current losses (resistive plus eddy),
R_{dc} is winding dc resistance corrected to reference temperature.

If laboratory power is not sufficient or power control adjustment is not fine enough to carry out a test at full current, testing at a current level down to 90% of I_{test} is permissible. The measured temperature rise shall be corrected using Equation (17).

12.4.2 Temperature-rise test—general (common) test procedures

12.4.2.1 Assembly for test

Reactors shall be completely assembled. For dry-type air-core smoothing reactors, the temperature-rise test need not be performed on the contract support structure (see 12.4.4.8).

12.4.2.2 Temperature of surrounding air

The temperature of the surrounding air, ambient temperature, shall be determined by at least three thermocouples, or thermometers, spaced uniformly around the reactors under test. They should be located at about one half of the height of the reactor, and at a distance of 1–2 m from the reactor. They should be protected from drafts and abnormal heating.

12.4.2.3 Containers for thermometers

To reduce to a minimum the degree of error due to time lag between the temperature of the reactors and the variations in the ambient temperature, the thermocouples, or thermometers, shall be placed in suitable containers that shall have such proportions as will require not less than 2 h for the indicated temperature within the container to change 6.3 °C if suddenly placed in air which has a temperature 10 °C higher, or lower, than the previous steady-state indicated temperature within the container.

12.4.2.4 Temperature rise of the winding

The temperature rise of the winding shall be determined by the resistance method, or by thermometer when so specified.

12.4.3 Temperature-rise test on oil-immersed smoothing reactors

12.4.3.1 General

The top-oil temperature shall be measured by a thermocouple or alcohol thermometer immersed approximately 50 mm below the top-oil surface.

The average temperature of the oil shall be determined when the average temperature method is used. The average oil temperature is equal to the top-oil temperature minus one half the difference in temperature of the moving oil at the top and the bottom of the cooling means, as determined by measurements.

For smoothing reactors with external cooling means, this temperature difference may be closely approximated by careful determination of the temperature on the external surface of the oil inlet and oil outlet of the cooling means by the use of thermocouples. However, it is preferable if oil wells are provided within the oil inlet and outlet pipe(s) as greater accuracy may be provided in the determination of the average oil temperature.

12.4.3.2 Ambient temperature

The ambient temperature shall be taken as that of the surrounding air, which should be not less than 10 °C or more than 40 °C. For ambient temperatures within this range, no correction factor shall be applied.

If suitable correction factors are available, temperature tests may be made with ambient temperature outside the range specified—temperatures lower than 10 °C and higher than 40 °C.

12.4.3.3 Methodology

The average winding temperature rise over the ambient temperature is the temperature of the winding corrected to the instant of shutdown, minus the ambient temperature.

NOTES:

1—See Clause 11 of IEEE Std C57.12.90-1999 for additional background information on temperature-rise test conditions and methodology.

2— Since core losses do not contribute to winding temperature rise, they may be deducted from the total harmonic losses (P_{htot}) in Equation (13).

12.4.4 Temperature-rise test on dry-type smoothing reactors

12.4.4.1 Determination of temperature rise of metal parts

The temperature rise of metal parts (other than the winding conductor) in contact with, or adjacent to insulation, and of other metal parts, shall be determined by thermocouple, conventional thermometer, or fiber optic thermometer, when required.

12.4.4.2 Ultimate temperature rise

The ultimate temperature rise is considered to be reached when the temperature rise does not vary more than 1 °C during the last hour and the testing time is at least five times the thermal time constant of the reactor. If the thermal time constant is incorrectly estimated and the duration of the temperature-rise test is not sufficient (based on 5 times the thermal time constant), then the temperature-rise test is to be repeated.

12.4.4.3 Measurement of surface temperature

Thermocouples, temperature labels, conventional thermometers, or fiber-optic thermometers may be used to measure surface temperature. It should be noted that the use of thermocouples can be hazardous due to parts being at high voltage.

12.4.4.4 Acceleration of the duration of the temperature-rise test

It is permissible to shorten the time required for the test by the use of initial overloads, restricted cooling, or any other suitable method. This procedure will not affect the determination of thermal time constant as the *cooling down* thermal time constant is identical to the *heating up* thermal time constant. It should be noted that the thermal time constant is required in order to determine the end point of the temperature-rise test (duration ≥ five times the thermal time constant). It is also preferable to have knowledge of the thermal time constant before the temperature-rise test commences or determine the thermal time constant from the heating up period. This will reduce the risk of having to repeat the temperature-rise test if it is terminated too soon as determined by a measurement of the cooling down thermal time constant.

12.4.4.5 Correction for ambient air temperature

When the ambient air temperature is other than 30 °C, a correction shall be applied to the temperature rise of the winding by multiplying it by the correction factor, C, which is given by the ratio

$$C = \frac{T_k + 30\ ^\circ\mathrm{C}}{T_k + T_a} \tag{14}$$

where

T_k = 234.5 °C for copper
= 225 °C for aluminum,
T_a is ambient air temperature (°C).

12.4.4.6 Temperature-rise test by temperature indicating device

When temperature-rise tests by temperature-indicating devices (thermocouple, thermal sensor, etc.) are required, place at least one temperature-indicating device in each winding group so that it is in contact with the coil winding. It is important that the temperature-indicating devices be placed in the cooling air ducts in such a manner as to indicate the winding temperature without restriction of the ventilation. Once the temperature rise has become constant, the test voltage and current should be removed. Immediately thereafter, the coil temperature indicating devices, and any other temperature-indicating devices, should be read continually in rotation until the temperature begins to fall. If any of the temperature-indicating device temperatures are higher than those observed during the run, the highest temperature should be recorded as the final temperature reading.

If the smoothing reactor is fitted (supplied) with *top hats*, enclosures, *electrostatic* shields (*dummy package*), or any other type of passive mitigation geometry, for example for sound suppression purposes, the complete assembly shall be installed for the temperature-rise test. If sound mitigation treatment (shielding) is a possible field installed option, consideration should be given to simulating its effect during the temperature-rise test.

12.4.4.7 Measurement of hot spot

Since hot spot determines service life, the measurement of hot spot during the *heat run* type test is important. Dry-type air-core smoothing reactors usually employ fully encapsulated windings. Therefore, direct access to the winding is not possible for the measurement of hot-spot temperatures during the *heat run* test. However, it is possible to measure winding surface temperature with some degree of accuracy. Such winding surface temperature measurements are essentially a measurement of winding hot spot due to the fact that the winding encapsulation medium is thin compared to the winding conductor cross section.

Winding hot spot can be measured using thermometers, thermocouples, or fiber-optic probes. In all cases, the method for fixing of the temperature-measuring device to the surface of the winding is extremely critical. Silicone rubber sealant compound or similarly based adhesive systems offer the best performance due to their bonding capabilities at high temperatures and thermal insulating properties. The amount of silicone rubber sealant used is important. Sufficient material should be employed to bond the thermometer bulb to the surface in such a manner that the bulb registers only surface temperature and not air temperature. The same holds true for thermocouples or fiber-optic probes.

Another important criteria is to ensure that the measuring device or the bonding system does not impede or influence the flow of cooling air.

A hot-spot measurement should be made for each encapsulated winding group in the reactor under test.

Hottest-spot location and hence measurement-point location is typically in the last turns of the upper winding end. Exact location, and hence the temperature measuring device placement decision, should be based on the manufacturer’s detailed knowledge of the product.

Hottest-spot temperature rise should not exceed the limits specified in Table 3, taking into consideration the insulation temperature class.

12.4.4.8 Ventilation clearance

It is not necessary to perform the temperature-rise test on the contract support structure since, due to heights involved, performance of the heat run could be extremely difficult. However, a minimum air clearance is required to ensure realistic results, typically, at least 1.5 times the winding total winding section or build. Additionally, the height of an alternative support structure shall be equal to or less than the height of the contract support structure.

12.4.5 Correction back to shutdown

12.4.5.1 Correction back to shutdown, cooling curve method

Take a series of at least four, preferably more, resistance readings on the winding, and record the time after shutdown for each reading.

12.4.5.2 Readings

The readings should be time-spaced to assure accurate extrapolation back to shutdown.

12.4.5.3 Reading time

The overall reading time should exceed 4 min and may extend considerably beyond. If the thermal time constant measurement is required, the dc resistance readings may be extended for a sufficient time. This method is an alternative if an overload is applied during the beginning of the heat run test.

12.4.5.4 First reading

The first reading on the winding should be taken as quickly as possible after shutdown, but not before the measuring current has become stable, and must be taken within 4 min.

12.4.5.5 Resistance vs. time plot

Plot the resistance time data on suitable coordinate paper, and extrapolate the curve back to the instant of shutdown.

12.4.5.6 Resistance at shutdown

The resistance value so obtained shall be used to calculate the average winding temperature at the instant of shutdown.

12.4.5.7 Resumption of temperature-rise test

If necessary, the temperature-rise test may be resumed so that the first readings on the winding may be completed within the required 4 min.

12.4.6 Average measured winding temperature determined by the hot-resistance method

The average measured temperature of the winding conductor may be determined by either of the following equations

$$\theta = \frac{R}{R_o}(T_k + \theta_o) - T_k \tag{15}$$

$$\theta = \frac{R - R_o}{R_o}(T_k + \theta_o) + \theta_o \tag{16}$$

where

θ is temperature (°C) corresponding to hot resistance, R,
R is hot resistance,
R_o is cold resistance determined in accordance with the rules in this standard,
T_k = 234.5 °C for copper
= 225 °C for aluminum,
θ_o is temperature (°C) corresponding to cold resistance, R_o.

12.4.7 Winding-temperature correction for reduced current

When the input test current is below the full value of the thermal equivalent current as calculated by Equation (13), but not less than 90%, the temperature rise of the winding shall be measured by the resistance method when steady-state conditions have been reached, and corrected to full thermal equivalent current, by the formula

$$\theta_n = \theta(I_{\text{test}} / I_{\text{reduced}})^2 \tag{17}$$

where

θ_n is average temperature rise at full test current,
θ is average temperature rise at reduced test current,
I_{test} is full dc test current,
I_{reduced} is reduced test current.

The use of an exponent of 2 is conservative and worst-case. If the manufacturer wishes to use another exponent (1.8 and 1.6 are typical), a second heat run at 80% of the test current should be performed in order to determine the specific exponent of the tested reactor.

12.4.8 Correction of observed temperature rise for variation in altitude

12.4.8.1 Altitudes less than 1000 m

When tests are made at an altitude not exceeding 1000 m above sea level, no altitude correction shall be applied to the temperature rise.

12.4.8.2 Smoothing reactors installed at altitudes exceeding 1000 m

When a smoothing reactor that is tested at an altitude less than 1000 m is to be operated at an altitude in excess of 1000 m, it shall be assumed that the observed temperature rise in service will increase in accordance with the following relation

Increase in temperature rise at altitude *A* in m is equal to

$$\text{Observed rise } X\left(\frac{A}{A_0} - 1\right)F \tag{18}$$

where

A_0 is 1000 m,
F is empirical factor, as follows

Method of cooling	Empirical factor, *F*
Oil-immersed, self-cooled (ONAN)	0.04
Dry-type, self-cooled	0.05
Oil-immersed, forced-cooled (ONAF)	0.06

The observed rise in Equation (18) is

a) Top-oil temperature rise, or average-oil temperature rise, and winding-temperature rise over the ambient temperature for oil-immersed smoothing reactors

b) Winding-temperature rise over the ambient temperature for dry-type smoothing reactors

12.4.9 Correction of observed temperature rise for unusual ambient temperature

Where an alternate reference temperature other than 30 °C is desired due to unusual site ambient temperature, the alternate reference temperature may be substituted directly into Equation (14) in place of the 30 °C value.

12.5 Dielectric tests for oil-immersed smoothing reactors

12.5.1 Dielectric tests at the factory

12.5.1.1 General

The purpose of dielectric tests in the factory is to demonstrate that the smoothing reactor has been designed and constructed to withstand the specified insulation levels.

Unless otherwise specified, dielectric tests shall be made in accordance with IEEE Std 4-1995.

The factory dielectric tests must be performed after the loss test and the temperature-rise test (if applicable).

12.5.1.2 Additional requirements for oil-immersed smoothing reactors

12.5.1.2.1 Assembly of oil-immersed smoothing reactors

Oil-immersed smoothing reactors, including bushings, terminal compartments, radiators, cabinets, etc. shall be assembled prior to performing routine and design dielectric tests on the first unit of an order. However, assembly of items such as radiators or cabinets, which do not affect internal dielectric stresses, is not necessary for routine dielectric tests on the remaining units of an order. Bushings shall, unless otherwise authorized by the purchaser, be those supplied with the smoothing reactor.

12.5.1.2.2 Tests on bushings for oil-immersed smoothing reactors

When tests are required on bushings separate from the smoothing reactor, the tests shall be made in accordance with IEEE Std C57.19.03-1996 or otherwise agreed upon between the manufacturer and purchaser.

12.5.1.3 Test requirements

The levels and other test parameters shall be as outlined in Clause 8 and Clause 11 of this standard or as otherwise specified.

12.5.1.4 Measurement of test voltages

Unless otherwise specified, the dielectric test voltages shall be measured or applied, or both, in accordance with IEEE Std 4-1995.

12.5.2 Switching impulse tests

12.5.2.1 Test procedures

The ends of the winding shall be connected together and the switching impulse test shall consist of applying a switching impulse wave between the winding and ground.

When a switching impulse withstand level is specified across the winding, a switching impulse test across the windings shall be performed. In some cases, particularly when the inductance is low, the energy available from the impulse generator may not be sufficient to obtain the required waveshape. In any case, a minimum available energy of 50 kJ is desirable. See 12.6.4 for more background information.

12.5.2.2 Number of tests

The test series shall consist of one reduced voltage at 50%–70% of the specified test level followed by three full voltage transients at the specified test level.

12.5.2.3 Oil temperature

Switching impulse tests may be performed at oil temperatures assumed under normal operation or at the temperatures attained under the conditions of routine tests.

12.5.2.4 Switching impulse waves

12.5.2.4.1 Polarity

For the switching impulse test, negative polarity is usually employed. If positive or both polarities are required for the switching impulse test, the purchaser must notify the manufacturer at the tender stage.

12.5.2.4.2 Wave shape

12.5.2.4.2.1 Switching impulse test of insulation to ground

A standard 250 μs × 2500 μs switching impulse wave shall be applied between the winding (with the two terminals connected together) and ground.

12.5.2.4.2.2 Switching impulse test across the reactor

The switching impulse voltage wave shall have a crest value in accordance with the assigned insulation level, subject to a tolerance of ±3%, and shall exceed 90% of the crest value for at least 200 μs. The actual time to crest shall be greater than 100 μs and the time to the first voltage zero on the tail of the wave shall be at least 1000 μs. The energy available from the impulse generator may not be sufficient to produce the required wave shape, especially for lower inductance smoothing reactors. In cases where the specified wave shape is not achievable, the manufacturer must provide, at bid stage, to the purchaser, details of the achieveable wave shape for his approval.

12.5.2.4.3 Time to crest

The actual time to crest shall be defined as the time interval from the start of the transient to the time when the maximum amplitude is reached.

12.5.2.4.4 Time to first voltage zero

The time to the first voltage zero on the tail of the wave shall be defined as the time interval from the start of the transient to the time when the first voltage zero occurs on the tail of the wave.

12.5.2.4.5 Ninety-percent time

A smooth wave sketched through any oscillations on the switching impulse voltage oscillogram may be used to determine the time that the applied wave is in excess of 90% of the specified crest value.

12.5.2.5 Failure detection

A digital test record shall be taken of each applied voltage transient. The test is successful if there is no sudden collapse of voltage indicated on the digitally recorded waveshape. For switching impulse tests applied across the windings, successive digitally recorded wave shapes may differ because of the influence of magnetic saturation on impulse duration. This phenomena does not occur for switching impulses applied between winding and ground.

12.5.3 Lightning-impulse test procedures

Lightning-impulse tests shall consist of and be applied in the following order: one reduced full wave, one full wave, one reduced (optional) chopped wave, two (optional) chopped waves, and two full waves. The time interval between application of the last chopped wave and the final full wave should be minimized (preferably within 10 min) to avoid recovery of dielectric strength if a failure were to occur prior to the final full wave.

Depending on system requirements, the test voltage level at one terminal may differ from that of the opposite terminal.

For guide information on impulse testing techniques, interpretation of oscillograms, and failure detection criteria, see IEEE Std C57.98-1993.

12.5.3.1 General

12.5.3.1.1 Oil temperature

Lightning impulse tests may be performed at oil temperatures assumed under normal operation or at the temperatures attained under the conditions of routine tests.

12.5.3.1.2 Full-wave test

The test wave rises to crest in 1.2 µs and decays to half of its value in 50 µs from the virtual time zero. The crest value shall be in accordance with the assigned BIL, subject to a tolerance of ±3%, and no flashover of the bushing or test gap shall occur. The tolerance on time to crest should normally be ±30% and the tolerance on time to half of crest shall normally be ±20%. However, as a practical matter, the impedance of some windings may be so low that the desired time to the 50% voltage point on the tail of the wave cannot be obtained with available equipment. In such cases, shorter waves may be used. Several alternatives can be used to improve the time to the 50% voltage point (e.g., use of parallel stages in the impulse generator). The time to the 50% voltage point on the tail of the wave is basically a function of the available energy from the impulse generator. Therefore, in cases where it is not possible to achieve the 50-µs tail and to insure that an adequate test is obtained, the available energy of the generator, with the connection used, shall be as high as possible—if attainable, a minimum available energy of 50 kJ is desirable.

For convenience in measurement, the time to crest may be considered as 1.67 times the actual times between points on the front of the wave at 30% and 90% of the crest value. The virtual time zero can be determined by locating points on the front of the wave at which the voltage is, respectively, 30% and 90% of the crest value and then drawing a straight line through these points. The intersection of this line with the time axis (zero-voltage line) is the virtual time zero.

When there are oscillations on the front of the waves, the 30% and 90% points shall be determined from the average, smooth wave front sketched in through the oscillations. The magnitude of the oscillations preferably should not exceed 10% of the applied voltage.

When there are high-frequency oscillations on the crest of the wave, the crest value shall be determined from a smooth wave sketched through the oscillations. When the period of these oscillations is 2 µs or more, the actual crest value shall be used.

12.5.3.1.3 Reduced full-wave test

This wave is the same as a full wave except that the crest value shall be between 50% and 70% of the full-wave value.

12.5.3.1.4 Chopped-wave test

This wave is also the same as a full wave except that the crest value shall be at the required higher level and the voltage wave shall be chopped at or after the required minimum time to sparkover. In general, the gap or other equivalent chopping device shall be located as close as possible to the terminals of the test object without disrupting its electric field distribution. The impedance of the chopping circuit shall be minimized and shall be limited to that of the necessary leads to the gap. If the undershoot during chopping exceeds 50% of the voltage at the instant of chopping, the distances can be increased but should not exceed a lead length greater than the height of the test object. If movement of the chopping circuit does not reduce the undershoot to less than 50%, it may be permissible, based on agreement with the purchaser, for the manufacturer to add resistance to limit the amount of overswing to the opposite polarity to 50% of the amplitude of the chopped wave. It should be noted that the use of a resistor may reduce the severity of the chopped-wave test by reducing the slope of the wave shape after chopping. As per IEEE Std 4-1995, the undershoot should, ideally, depend only on the characteristics of the test object (internal capacitance and damping).

12.5.3.1.5 Wave polarity

The test waves are normally of negative polarity to reduce the risk of erratic external flashover in the test circuit.

12.5.3.1.6 Impulse test records

All impulses applied to a smoothing reactor shall be recorded by digital transient recorder, unless their crest voltage is less than 40% of the full-wave level. For all full-wave and reduced full-wave impulses, these digital test records shall include voltage test records for all impulses and, for the impulse tests when the opposite terminal of the winding is grounded, ground-current test records. Sweep times should be in the order of 5 µs to 10 µs for chopped-wave tests, 50 µs to 100 µs for full-wave tests, and 100 µs to 600 µs for ground-current measurements (when applicable).

When reports require digital test records, those of the first reduced full-wave voltage and current, the first full wave impulse, the last two chopped-wave tests, and the last full-wave of voltage and current shall represent a record of the successful application of the impulse test to the smoothing reactor. All digital test records shall be included in the test report.

12.5.3.2 Connections for lightning impulse tests of line terminals

Each end of the winding shall be impulsed with the other grounded. The full-wave impulse voltage level for this test will be the highest BIL level in 6.1 and 6.5.1.

If a lower BIL level is specified across the winding than that specified to ground, then a second series of impulse tests shall be carried out with both terminals connected together and the impulse applied between the connected terminals and ground.

12.5.3.3 Detection of failure during impulse test

Because of the nature of impulse-test failures, one of the most important matters is the detection of such failures. There are a number of indications of insulation failure.

12.5.3.3.1 Ground-current digital test records

In this method of failure detection, the impulse current in the grounded end of the winding tested, when available, is measured by means of a digital transient recorder connected across a suitable shunt inserted between the grounded end of the winding and ground. Any differences in the waveshape between the reduced full wave and the final full wave detected by comparison of the two current digital test records may be indications of failure or deviations due to noninjurious causes. They should be fully investigated and explained by a new reduced wave and full-wave test. Examples of probable causes of different wave shapes are operation of protective devices, core saturation, or conditions in the test circuit external to the smoothing reactor.

The ground-current method of detection is not suitable for use with chopped-wave tests.

12.5.3.3.2 Other methods of failure detection

Other methods of failure detection include the following.

a) *Digital data acquisition systems:* Digital test systems provide the opportunity for various test analysis methodologies e.g., transfer function, etc.

b) *Voltage oscillograms:* Any unexplained differences between the reduced full wave and final full wave detected by comparison of the two voltage digital test records, or any such differences observed by comparing the chopped waves to each other and to the full wave up to the time of chopping, are indications of failure.

c) *Failure of gap to sparkover:* In making the chopped-wave test, failure of the chopping gap, or any external part to sparkover, even though the voltage digital test record shows a chopped wave, is a definite indication of a failure within the smoothing reactor.

d) *Noise:* Unusual noise within the smoothing reactor at the instant of applying the impulse is an indication of failure. Such noise should be investigated.

12.5.4 DC applied voltage test with partial discharge measurement

12.5.4.1 Temperature of the oil

For the dc applied voltage test, the temperature of the oil shall be 20 °C ± 10 °C and the ambient temperature shall be between 10 °C and 40 °C.

12.5.4.2 Polarity

Positive dc polarity shall be used.

12.5.4.3 Test procedure

No preconditioning of the smoothing reactor insulation structure at a lower dc voltage is permitted prior to the dc applied test. Pumps (if used) should not be running during the test. The dc voltage shall be brought up to full value in not more than 1 min and shall be held for a period of at least 120 min, but not greater than 150 min, depending on the partial discharge criteria described in 12.5.4.4, after which the voltage shall be reduced to zero within 1 min.

CAUTION—After a dc voltage test is complete, the insulation structure retains a considerable electrical charge. For safety reasons all terminals should be grounded after the dc test for a period of time.

12.5.4.4 Acceptance criteria

Failure may be indicated by an audible sound such as a thump, or a sudden increase in test current. Oil-immersed reactors may also experience the presence of smoke and bubbles rising in the oil. Any such indication shall be carefully investigated by observation, by repeating the test, or by other tests to determine if a failure has occurred.

Partial discharge measurements should be performed throughout the entire dc applied voltage test. In terms of interpreting the partial discharge measurements, the results shall be considered acceptable and no further partial discharge tests required when during the last 30 min of the test no more than 30 pulses > 2000 pC are noted with no more than 10 pulses in the last 10-min period. If the number of pulses exceeds 30 during the last 30 min or 10 pulses in the last 10 min of the initial 120-min period, the test may be extended by another 30-min observation period. There may be only one 30-min extension, and the reactor shall be accepted when the number of pulses in such a 30-min period is no more than 30 with no more than 10 pulses in the last 10 min.

When no breakdown occurs, and unless very high partial discharges are sustained for a long time, the test is regarded as nondestructive. A failure to meet the partial discharge criterion shall, therefore, not warrant immediate rejection but lead to consultation between end user and manufacturer about further investigation. It is recommended to conduct the dc applied voltage test with ultrasonic transducers installed on the smoothing reactor tank. Those transducers may help to distinguish internal or external discharges.

12.5.5 Polarity-reversal test with partial discharge measurements

12.5.5.1 Temperature of the oil

The average temperature of the oil shall be 20 °C ± 10 °C and the ambient temperature shall be between 10 °C and 40 °C.

12.5.5.2 Test procedure

All bushings should be grounded for a minimum of 2 h prior to the test. No preconditioning of the smoothing reactor insulation structure at a lower dc voltage is permitted prior to the polarity reversal test. Pumps (if used) should not be running during the polarity reversal test. The voltage shall be increased to the full polarity-reversal test level (negative polarity) within 1 min and held for a period of 90 min, after which the voltage shall be reduced to zero, polarity reversed, and voltage increased to full polarity reversal test level (positive polarity). The complete reversal shall be accomplished as quickly as possible, and must be performed within 2 min. The completion of the reversal is defined as the time when the voltage has reached its 100% test value. After being held at the positive polarity value for another 90 min, the voltage is reversed once again to the same level at negative polarity and maintained for 45 min. This reversal should also be performed as quickly as possible, and must be accomplished within 2 min. When the entire polarity reversal sequence is completed the voltage shall be returned to zero within 1 min.

CAUTION—Although the voltage levels are lower for the polarity-reversal test than the dc voltage test, substantial electrical charge can remain on the insulation structure within the reactor. For safety reasons, all bushings should be grounded after the polarity-reversal test for a period of time. Subsequent partial discharge measurements may also be affected unless the insulation structure is adequately discharged.

12.5.5.3 Acceptance criteria

Failure may be indicated by an audible sound such as a thump, a sudden increase in test current, or the inability of the power supply to maintain a dc voltage. Oil-immersed smoothing reactors may also experience the presence of smoke and bubbles rising in the oil.

Partial discharge measurements shall be performed throughout the entire polarity reversal. Partial discharge levels must be monitored and documented for the full duration of the polarity reversal test, reversal duration, and for the final 15 min of the final 45-min reversal duration. In terms of interpreting the partial discharge measurements, the results shall be considered acceptable and no further partial discharge tests required when during the 30 min following each reversal no more than 30 pulses > 2000 pC are noted, with no more than 10 pulses > 2000 pC occurring in the last 10 min. Because some discharge activity is normal during polarity reversals, partial discharge measurements made during the first minute after completion of the last polarity reversal shall be disregarded.

When no breakdown occurs, and unless a very high number of partial discharge pulses exceeding 2000 pC are detected and sustained for a long time, the test is considered nondestructive. A failure to meet the partial-discharge criteria shall, therefore, not warrant immediate rejection of the reactor but lead to consultation between the purchaser and manufacturer about further investigation.

It is recommended to conduct the polarity-reversal test with ultrasonic transducers installed on the smoothing reactor tank. These transducers may help to distinguish between internal or external sources.

12.5.6 AC applied voltage test and ac power test for oil-immersed smoothing reactors

12.5.6.1 AC applied voltage test to ground with partial discharge detection for oil-immersed smoothing reactors

12.5.6.1.1 Duration, frequency, and connections

A normal power frequency such as 60 Hz shall be used and the duration of the test shall be 60 min.

The winding being tested shall have all its parts joined together and connected to the line terminal of the testing transformer. All other parts (including core, if used, and tank) shall be connected to ground and to the other terminal of the testing transformer.

Equipment and techniques used for measurement of partial discharge shall be as defined in 12.5.7.1.

NOTE—The use of equipment to detect partial discharge acoustically is also recommended.

12.5.6.1.2 Relief gaps

A relief gap set at a voltage 10% or more in excess of the specified test voltage may be connected during the low-frequency applied-voltage test.

12.5.6.1.3 Temperature of the oil

The ac applied voltage test may be performed at an average oil temperature of 20 °C ± 10 °C and the ambient temperature shall be between 10 °C and 40 °C.

12.5.6.1.4 Test procedure

The voltage shall be started at one quarter or less of the full value and brought up gradually to full value in not more than 15 s. After being held for the time specified, it should be reduced gradually (in not more than 5 s) to one quarter or less of the maximum value and the circuit opened.

12.5.6.1.5 Acceptance criteria

Failure may be indicated by an audible sound such as a thump, or a sudden increase in test current. Oil-immersed reactors may also experience the presence of smoke and bubbles rising in the oil. Any such indication shall be carefully investigated by observation, by repeating the test, or by other tests to determine if a failure has occurred.

Partial discharges (including background noise) measured during the ac applied voltage test shall not exceed 500 pC and shall not increase by more than 100 pC from the initial reading. If the partial discharge (including background noise) increases by more than 100 pc, but is still less than 500 pC, the test may be extended to determine whether the partial discharge level will stabilize or decrease.

Partial discharge measurement methodology and test equipment should be as outlined in 12.5.7.1. The use of equipment to detect partial discharges acoustically is also recommended.

12.5.6.2 AC power test between terminals with Q-factor measurements for oil-immersed smoothing reactors

12.5.6.2.1 Duration, frequency, and connections

The frequency of the ac power supply shall be between 50 Hz and 1000 Hz and the duration of the test shall be 5 min.

The HV end of the ac power frequency supply shall be connected to one terminal of the smoothing reactor, the other terminal being connected to the grounded point of the ac power frequency supply. All other parts (including core, if used, and tank) shall be connected to ground and to the grounding point of the ac power frequency supply.

12.5.6.2.2 Temperature of the oil

The ac power test between terminals may be performed at oil temperatures assumed under normal operation or at the temperatures attained under the conditions of routine tests.

12.5.6.2.3 Test procedure

The ac test voltage shall be two times the maximum specified continuous harmonic voltage drop. The ac voltage to be applied across the terminals is given by

$$E_{\mathrm{AC}} = 2.0\Sigma I_h Z_h \tag{19}$$

where

I_h is specified continuous harmonic current at harmonic frequency, f_h,
Z_h is impedance of smoothing reactor at harmonic frequency, f_h,
h is harmonic order where $h = 1–49$.

12.5.6.2.4 Failure detection

Failure may be indicated by an audible sound such as a thump, or a sudden increase in test current. Oil-immersed reactors may also experience the presence of smoke and bubbles rising in the oil. Any such indication shall be carefully investigated by observation, by repeating the test, or by other tests to determine if a failure has occurred.

The primary method of determining if a failure has occurred is to compare the Q-factor or harmonic losses measured during the ac power test to those measured prior to the dielectric tests.

12.5.7 Partial discharge measurements

12.5.7.1 Partial discharge measurements for ac tests

Techniques for performing partial discharge measurements on the ac tests for smoothing reactors are similar to those described in IEEE Std C57.113-1991, while general principles are covered in ANSI C68.3-1976, IEC 60270 (1981-01), and IEC 60076-3 (2000-03).

12.5.7.2 Partial discharge measurements for dc tests

Apparent charge measurements are used for the investigation of partial discharges during the dc voltage and polarity-reversal tests. Partial discharges under pure direct voltage occur in the form of large single pulses at random intervals. For the purpose of these tests, a pulse is defined as a partial discharge with an apparent charge according to IEC 60270 (1981-01) of 2000 pC or higher. Measuring circuits and detailed test procedures for ac tests, which may be applied as far as possible for these dc tests, are described in IEEE Std C57.113-1991, while general principles are covered in ANSI C68.3-1976 and IEC 60076-3 (2000-03) (see Annex A).

12.5.8 Dielectric tests in the field

Periodic dielectric tests are not recommended because of the severe stress imposed on the insulation.

For oil-immersed smoothing reactors, a low-frequency applied-voltage test to ground shall be used. The line-to-ground voltage stress imposed shall not exceed 80% of the value given by Equation (4). The duration of the test shall not exceed 60 min.

If an applied dc test is performed, it shall not exceed 80% of the factory dc applied test voltage given in Equation (1). The duration of the test shall last at least 30 min, but shall not exceed 60 min.

12.6 Dielectric tests for dry-type smoothing reactors

12.6.1 General

Unless otherwise specified, dielectric tests shall be made in accordance with IEEE Std 4-1995.

12.6.2 Factory dielectric tests

In general, dielectric tests are carried out to simulate in-service conditions and as a quality check. More specifically, the purpose of dielectric tests at the factory is to demonstrate that the reactor has been designed and constructed to withstand the specified insulation levels.

Dry-type smoothing reactors shall be completely assembled prior to making dielectric tests. For design tests, this includes support insulators, insulator extension brackets, and corona electrodes, when supplied as part of the contract or as agreed to by purchaser and manufacturer, especially if there are dielectric-clearance limitations in the test laboratory.

12.6.3 Lightning-impulse tests

12.6.3.1 General

For the routine impulse test, it is not necessary to perform the test with the reactor mounted on the contract support structure. Design and routine impulse tests must be carried out using a digital impulse test system.

Test levels shall be as specified by the purchaser.

The primary focus of routine impulse testing is quality verification. The use of a digital impulse test system significantly improves the ability to verify winding insulation integrity over that achievable with analog impulse test systems. The routine lightning impulse test should be carried out in the test sequence as follows:

- One reduced lightning impulse test
- Three full impulse tests at positive and negative polarity on both terminals

It should be noted that a further verification of the successful completion of dielectric tests is achieved by performing the 1 h ac power test following the dielectric test sequence.

Impulse-design tests primarily focus on suitability of design for in-service conditions. In the case of impulse design tests on dry-type air-core smoothing reactors, the following rationale should be taken into consideration. Smoothing reactors are considered to be strategic equipment in an HVDC substation and it is important that the confidence level obtained during impulse-design tests is consistent with the type of insulation system being used. For the windings of dry-type air-core smoothing reactors, two types of insulation systems are mixed (employed): internal insulation (conductor insulation system) and external insulation (air). If an external insulation system design of sufficient safety factor is employed, the inherent probabilistic withstand capability of the external air portion of the winding insulation system will not be a significant factor. Therefore, the issue of whether this portion of a dry-type air-core smoothing reactor insulation system is self restoring in nature is secondary. It should also be noted that specified dielectric design objectives and test levels, coupled with insulation coordination margins, address the issue of in-service factors, which may affect dielectric withstand.

Therefore, the recommended design impulse test procedure is consistent with dielectric test practice in other dry-type reactor standards and, in fact, in standards for other large scale power equipment. Procedure C in IEEE Standard 4-1995 provides the basis for the test rationale. The lightning impulse design test consists of three full waves of positive and negative polarity to each terminal—each set of three full waves preceded by a reduced wave of corresponding polarity.

If an optional chopped wave test is specified, the test sequence for each terminal is

- One reduced wave positive polarity
- Three full waves positive polarity
- One reduced wave negative polarity
- One full wave negative polarity
- One reduced chopped-wave negative polarity (optional)
- Two chopped waves negative polarity
- Two full waves negative polarity (the first one preferably within 10 min after the last chopped-wave test)

The requirements of the test are met if there are no disruptive discharges across the self-restoring part of the insulation system and if there are no indications of failure in the nonself-restoring part of the insulation system. If a flashover occurs, then 9 shots of that polarity are applied; no additional flashovers are allowed. It must also be demonstrated that the flashover did not damage the winding.

An optional procedure for the impulse design test is proposed to be consistent with other substation equipment employing mixed insulation systems (bushings, instrument transformers, circuit breakers, etc.). The objective is for the number of impulses applied to each terminal to be statistically significant. Procedure B in IEEE Std 4-1995 provides guidance.

Therefore, the lightning impulse design test should consist of one reduced wave of positive polarity and 15 full waves of positive polarity applied to each terminal.

If a chopped wave or other impulse test is required, the test sequence for each terminal should consist of:

- One reduced full wave positive polarity
- One full wave positive polarity
- One reduced full wave negative polarity
- One reduced chopped wave negative polarity (optional)
- Two chopped waves negative polarity
- One reduced full-wave positive polarity
- Fourteen full-waves positive polarity

The requirements of the test are met if there are no more than two disruptive discharges on the self-restoring insulation and if there are no indications of failure of the nonself-restoring insulation.

12.6.3.2 Test procedure

Lightning-impulse tests are required as a routine and design test for dry-type smoothing reactors.

The tests shall be applied to each terminal, one at a time, while the opposite terminal shall be grounded through a low-resistance shunt so that ground-current measurements can be made.

Depending on system requirements, the test voltage level at one terminal may differ from that of the opposite terminal.

The tests shall consist of, and be applied, in the order specified for routine or type tests in 12.6.3.1.

When an optional chopped-wave test is specified, impulse tests are generally applied in the following order: one reduced full wave, one full wave, one reduced chopped wave (optional), two chopped waves, and two full waves.

At least one reduced full wave must be applied first, other reduced full waves may be applied at any time during the test sequence, as deemed necessary.

If multiple coils are used to comprise one smoothing reactor, then based on a demonstration of the voltage sharing under voltage surge conditions, impulse tests can be carried out on separate coils at an appropriate test voltage level, to be agreed upon by the purchaser and manufacturer.

It is very critical to limit the amount of overshoot on the impulse test.

Refer to IEEE Std C57.98-1993 for guidance and information on impulse-testing techniques, interpretation of recorded wave shapes, and failure detection criteria.

12.6.3.3 Full-wave test

The wave shape shall be the standard 1.2/50 µs and the crest value shall be in accordance with the specified test level subject to a tolerance of ±3%. The tolerance on time to crest should be ±30% and the tolerance on time to one half of crest shall be ±20%.

In case the half value time cannot be obtained, the minimum available energy from the impulse generator shall be 50 kJ.

12.6.3.4 Wave polarity

For dry-type smoothing reactors, the test waves shall be of both positive polarity and negative polarity, unless otherwise specified.

12.6.3.5 Impulse digital test record

All impulses applied to a reactor shall be recorded by a suitable digital transient recorder, unless their crest value is less than 40% of the full-wave level. These digital test records shall include voltage records for all impulses and ground-current test records for all full-wave and reduced full-wave impulses. (See 11.3.8 of IEEE Std C57.16-1996 for additional information).

12.6.4 Switching impulse tests

12.6.4.1 Test procedures

Switching impulse tests are required as a design test for dry-type smoothing reactors. Functionally, the switching impulse can be applied both across the winding and to ground. However, for a switching impulse applied across the winding of a dry-type smoothing reactor, it is technically impossible for any test laboratory in existence today to obtain the required waveshape of 250 µs front and 2500 µs to 50% of crest value. For instance, in the case of a 200 kJ impulse generator used to test smoothing reactors of 200 mH and 1000 mH (which covers the typical range of inductance ratings), the best achievable wave shapes are 150 µs and 400 µs zero crossing, respectively. Another consideration is that BIL levels are at least 10% higher than switching impulse levels. For these reasons, the switching impulse across the winding of a smoothing reactor is classified as *other.* The number of shots should be as for the recommended impulse design test.

For the switching impulse type test to ground, there is no difficulty in obtaining the required waveshape. In the case of dry-type smoothing reactors, the major insulation to ground is provided by the support insulators. Therefore, this test is essentially a test of the support insulators. Since the insulators constitute a self-restoring insulation system, the test should be consistent with Procedure B in IEEE Std 4-1995, and the test should consist of 15 shots of positive polarity. Two flashovers are allowed.

The test shall be made under wet conditions as specified in IEEE Std 4-1995. If the test equipment cannot provide full wet conditions for all insulators simultaneously, the specified parameters for wet testing shall be met at least for one insulator of the support structure.

12.6.4.2 Wave polarity

For dry-type smoothing reactors the test waves shall be of positive polarity, unless otherwise specified.

12.6.4.3 Wave shape

The wave-shape shall be the standard 250/2500 μs and the crest value shall be in accordance with the specified test level subject to a tolerance of ±3%. The tolerance on time to crest should be ±20% and the tolerance on time to one half of crest shall be ±60%.

12.6.4.4 Failure detection

A digital test record shall be taken of each impulse wave. The test is considered successful if there is no collapse of voltage indicated on the digitally recorded wave.

12.6.5 DC withstand voltage test (wet)

Preferably, the test should be performed with the insulators arranged (under the reactor or equivalent *mock-up*) as in the in-service condition. This will more accurately simulate in service water (rain) runoff conditions. As an alternative, the test can be performed on at least one insulator of the support structure. However, if this methodology is employed, it shall be agreed upon by the purchaser and the manufacturer at bid stage. The precipitation shall be applied at least 30 min prior to testing and during the application of the test voltage in accordance with IEEE Std 4-1995. The test duration shall be 1 h and at a voltage level specified in 11.2.2. No flashover is allowed during the test.

12.6.6 DC pollution test on insulators

For dry-type air-core smoothing reactors, this is a test on the support insulators only. The system operating dc voltage is across the insulators. When required, the *other* dc pollution test shall be carried out on the insulators with a test procedure as specified by the purchaser. For more background information, see IEC/TR2 61245 (1993-10). ESDD level or other pollution severity criteria, such as pollution layer conductivity, leakage current magnitude etc., should be agreed upon between the purchaser and manufacturer.

12.6.7 RIV test

The purpose of this test is to determine the external corona activity of the smoothing reactor expressed in terms of RIV voltage measured at the terminals of the reactor.

12.6.7.1 Mounting arrangement and equipment

The test is usually performed with the smoothing reactor completely assembled and mounted on the support structure. The reactor terminals should be equipped with connectors (preferably the contract connectors) and bus bar configuration simulating the as installed condition. Apart from performing the test at applied dc voltage instead of ac voltage, the equipment and general method used in determining the radio-influence voltage shall be in accordance with the NEMA 107-1987.

NOTE—The RIV test can be performed (and has been performed for a number of projects) using the contract support structure and a suitable *mock-up* of important aspects of the reactor geometry. Performing this test in this manner is a matter for agreement between purchaser and manufacturer.

12.6.7.2 Test levels and duration

The test voltage levels shall be as specified by the customer. The test shall be done with dc voltage of both polarities, each for 30 min duration. During the last 10 min of each test period, the RIV meter shall not record consistently repeated readings above 2500 μV.

NOTE—By agreement between the purchaser and the manufacturer, the RIV test may be performed using ac voltage of suitable magnitude to simulate in-service dc operating voltage levels.

12.6.8 AC power test for dry-type smoothing reactors

This test is carried out at a level of ac current (50–1000 Hz) sufficient to produce a voltage drop across the terminals in excess of the voltage drop seen in-service due to the ripple current. The duration of this test is 5 min. The test voltage shall be calculated by

$$E_{\mathrm{AC}} = 2.0 \Sigma I_h Z_h \tag{20}$$

where

I_h is specified continuous harmonic current at harmonic frequency, f_h,
Z_h is impedance if smoothing reactor at harmonic frequency, f_h,
h is harmonic order, where $h = 1–49$.

NOTE—Due to laboratory limitations E_{AC} may not be attainable. In this case, the test value is to be agreed upon by the purchaser and the manufacturer.

For failure detection, the winding of the reactor shall be carefully observed for unusual noise, sparking, or smoke.

The purpose of the test is to provide a quality check of the winding insulation integrity after the dielectric tests. The basis of the test is to continuously apply a voltage stress to the turns insulation of twice the normal operating voltage and thus detect any incipient damage to the conductor insulation system resulting from the routine dielectric tests.

The primary method of determining if a failure has occurred is to compare Q-factor or harmonic losses measured during or after the ac power test to those measured prior to the dielectric tests.

12.7 Audible sound level test

12.7.1 General

The audible sound radiated by the reactor tank of an oil-immersed smoothing reactor is caused by both core and winding vibrations, which are coupled to the tank. The audible sound from dry-type smoothing reactors originates in the reactor winding from which it is radiated as airborne sound.

The sound radiated from a smoothing reactor depends on both dc and ripple current superimposed. Due to the interaction of dc and ac, the frequency spectrum of the audible sound consists primarily of a tone with the main frequency of the harmonic spectrum of the ripple current, usually 720 Hz, for a 12-pulse HVDC converter connected to a 60 Hz ac power system. Tones generated at other harmonic frequencies, 1440 Hz for example, may sometimes also be significant contributors to audible noise.

The sound level performance criteria usually applied on smoothing reactors is its A-weighted sound power level, which is derived from the measurement of the A-weighted sound pressure level.

The methods specified herein for measuring sound pressure levels or for calculating sound power levels are intended to be applicable to HVDC smoothing reactors tested indoors or outdoors at the factory.

Audible sound level testing can be expensive. As an alternative, calculations, backed by measurements in the lab or in the field on similar units, may be used to predict in-service acoustic levels.

12.7.2 Terminology

a) Ambient sound pressure level is the sound pressure level measured in the test facility without the reactor energized.

b) Sound pressure level, in decibels, is 20 times the logarithm to the base ten of the ratio of the measured sound pressure to a reference pressure of 20 µPa.

c) Sound power level, in decibels, is 10 times the logarithm to the base ten of the ratio of the emitted sound power to a reference power of 10^{-12} watt.

d) Semireverberant facility is a room with a solid floor and an undetermined amount of sound absorbing materials on the walls and ceiling.

12.7.3 Instrumentation

Sound pressure level measurements shall be made with instrumentation that meets the requirements of ANSI S1.4-1983 for type 2 m.

A suitable wind screen shall be used when the air velocity, due to winds, causes the readings to be in error.

Sound measuring instrumentation shall be calibrated before and after each measurement session. Further, it should be demonstrated prior to the measurement that the magnetic field of the reactor does not affect the readings of the sound-level meter. Should the calibration change by more than 1 dB, or should the readings change by more than 1 dB due to the magnetic field, the measurements shall be declared invalid.

12.7.4 Test conditions

Measurements should be made in an environment having an ambient sound pressure level at least 5 dB below the combined sound-pressure level of the reactor and the ambient sound pressure level. The corrections shown in Table 4 shall be applied to the combined reactor and ambient sound pressure level to obtain the reactor sound pressure level.

The reactor shall be located so that no acoustically reflecting surface is within 3 m of the measuring microphone, other than the floor or ground. Should the reactor be tested within a semireverberant facility, it should be located in an asymmetrical manner with respect to the room geometry. When reactor sound emissions are measured in an enclosed space, sound reflections from walls or other large objects can influence the results because the sound is essentially a discrete tone that may be affected by room acoustics, room geometry, or reflecting objects.

The smoothing reactor shall be completely assembled including all integral corona shields.

The installed mounting conditions of the reactor should be simulated as much as practicable.

12.7.5 Energization

As the sound level of an HVDC smoothing reactor is dictated by the interaction of dc with ac, it is critical to perform sound level measurements on smoothing reactors at dc with harmonic currents superimposed. Unless otherwise specified, it is recommended to consider only the main harmonic out of the harmonic current spectrum of the ripple current.

It is possible to load a smoothing reactor with dc current plus one major harmonic (at a time) in the lab using a two smoothing reactor bridge circuit. In this case, measured sound levels in the test lab will be representative of in service levels. If rated current values cannot be achieved, due to limitations of the test lab power supplies, it is possible to use calculations to extrapolate measured values of sound level; provided measured values of sound level are at least 5 dB above ambient level.

A test circuit as shown in Figure 6 may be used. This circuit requires two identical reactors that are acoustically isolated from each other. The ac source may be a semiconductor power converter with variable frequency. For maximum harmonic current driven through the reactors, the capacitors, C, are tuned for resonance at the harmonic frequency.

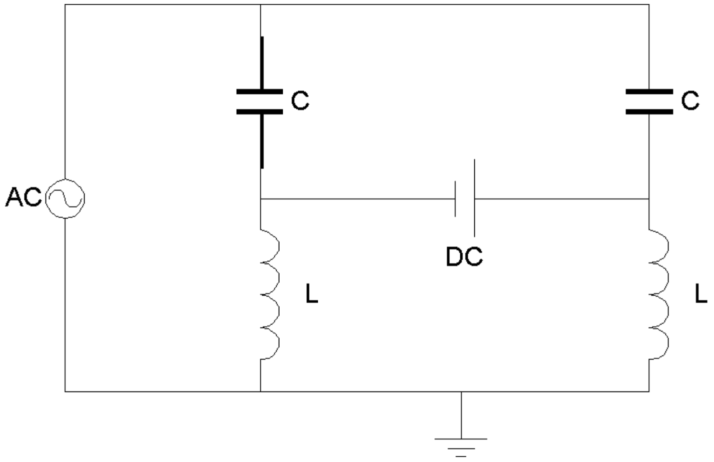


Figure 6—Test circuit for sound measurement

This test is applicable to both oil-immersed and dry-type smoothing reactors. Other test methods can be used, subject to agreement between the purchaser and manufacturer.

The reactor under test should be energized at rated dc current plus rated current of the main ripple harmonic superimposed. When available test power is insufficient for testing at rated current, the manufacturer must demonstrate to the purchaser’s satisfaction that reduced-current testing produces sufficiently accurate results when extrapolated to the rated current level.

For oil-immersed smoothing reactors with forced cooling, the test should be carried out with pumps and fans running.

12.7.6 Microphone positions

12.7.6.1 Oil-immersed smoothing reactors

The test procedure for determining the sound level of an oil-immersed smoothing reactor shall be in line with the procedure as described in Clause 13 of IEEE Std C57.12.90-1999.

12.7.6.2 Dry-type smoothing reactors

The reference sound producing surface of a dry-type smoothing reactor is its outside winding surface. For reactors with a winding less than 2.4 m (8 ft) tall, microphone locations shall be at midheight of the winding. For reactors greater than 2.4 m (8 ft) tall, microphone positions shall be at one-third and two-thirds winding height. In the plan view, the microphone locations shall be laid out clockwise, sequentially at intervals of 1 m along the circumference of a circle having its center at the geometric center of the reactor, and a radius equal to the reactor radius plus 3 m (10 ft). The first station will be on a radial line through the bottom terminal, or as close to it in the clockwise direction as is permitted to comply with minimum clearance distances to live parts.

12.7.7 Sound-level measurement

Sound-pressure levels shall be measured in conformance with 12.7.1, 12.7.3, 12.7.4, 12.7.5, and 12.7.6 using the sound-level-meter A-weighting characteristic.

12.7.8 Calculation of average sound pressure level

An average sound pressure level value, L_{pA}, shall be calculated from the measured values of the A-weighted sound pressure level, L_{pAi}, by using the following equation

$$L_{pA} = 10\log_{10}\left(\frac{1}{N}\sum_{i=1}^{N} 10^{0.1L_{pAi}}\right) \tag{21}$$

where

L_{pA} is average sound pressure level (dB),
L_{pAi} is measured sound pressure level at location, i (dB),
N is total number of measurement locations.

It should be noted that the above calculated value may have to be corrected for the following factors:

a) Ambient noise level

b) Acoustic influences of the location where sound readings are taken, e.g., reverberant properties of the test lab

Table 4—Correction to sound pressure level

Differences between average sound level of combined smoothing reactor plus ambient and average sound level of ambient (dB)	Corrections to be applied to average sound level of combined smoothing reactor plus ambient to obtain average sound level of smoothing reactor (dB)
5	1.6
6	1.3
7	1.0
8	0.8
9	0.6
10	0.4
Over 10	0.0

12.7.9 Calculation of A-weighted sound power level

The sound power level (L_{wA}) shall be computed

$$L_{wA} = L_{pA} + 10\log_{10}(S) \tag{22}$$

where

L_{wA} is sound power level (dB),
L_{pA} is average A-weighted sound pressure level, gained by measurement (dB),
S is measurement surface area in m^2.

The measurement surface area (S) is the area (in m^2) of a hypothetical envelope of the smoothing reactor on which the sound measurements are located. The determination of S is as follows.

For an oil-immersed smoothing reactor, S is defined in 13.5.4. of IEEE Std C57.12.90-1999 to be approximately

S = 1.25 × smoothing reactor height × measurement perimeter

For a dry-type smoothing reactor located near ground, the best estimation of the surface is a hemispherical shell. Thus, a dry-type smoothing reactor, S, is calculated as

$$S = 2\pi R_m^{\ 2}$$

where

R_m is the measurement radius.

12.8 Short-circuit withstand verification

In HVDC schemes employing overhead transmission lines or moderate lengths of cable, the smoothing reactor short-circuit current withstand requirement is determined by a worst case fault at the rectifier end of the link. Normal current surges have a significantly lower amplitude. However, in the case of a long HVDC cable, the worst current stress is due to the cable discharge current through the smoothing reactor when the inverter is blocked. The current amplitude during a commutation failure is almost the same. This means that for a smoothing reactor utilized in a scheme with a long HVDC cable it also must be verified that there is a sufficient capability to withstand repetitive current surge stresses and resistance to mechanical aging (fatigue). It is not sufficient to show the mechanical withstand capability based on a few shots of the same amplitude. Therefore, the purchaser shall not only specify the maximum current peak and associated wave-form, but also state the amplitude and frequency of occurrence of current surges of lower amplitude.

The typical specified short-circuit current of a smoothing reactor is a current wave that rises to crest in about 6–20 ms and decays to one half of crest value in about 6–20 ms. However, in the case where the current path is closed via a bypass-pair (shorting of valve bridge), the decay time will be much longer, in the order of 500 ms. The crest value and the wave shape shall be specified by the purchaser. The reactor shall be shown by design evidence to be capable of withstanding these short-circuit current requirements. Usually the mechanical and thermal stresses imposed by the short-circuit current are low, and it is suggested to verify the short-circuit performance of the reactor by analytical methods. In fact, if 80% of rated short-circuit current (64% of stresses) cannot be achieved in a test lab, then a verification of short-circuit performance by analytical calculations should be employed. These calculations must be authenticated by showing their correlation to tests performed on other reactors or models. More detailed information can be found in Annex C.

If short-circuit testing is requested, the test shall be performed with 60 Hz current providing a crest current equal to the specified crest value and approximating the I^2t of the specified current wave as close as possible. However, the I^2t value is not critical as the short-circuit test is primarily a mechanical test rather than a thermal test. IEEE Std C57.16-1996 should be consulted for short-circuit test set-up guidelines. Routine tests including dielectric tests, inductance, and loss measurements should be repeated after the short-circuit test. Correlation of before and after results should be consistent within measurement accuracy.

The equivalent power frequency power rating of smoothing reactors utilized on most large HVDC projects is such that commercial test laboratories may not be able to test the smoothing reactor at full rated short-circuit power. At the time of the writing of this standard, Annex D contains background information on typical laboratory short-circuit capability and information required in an analytical verification of short-circuit capability.

Therefore, due to limitations of test laboratories, the normal method of short-circuit withstand verification is by calculation.

12.9 Capacitor discharge test

The capacitor discharge test simulates in-service fault conditions: line discharge or dc filter capacitor bank discharge. This test is applicable to both oil-immersed and dry-type air-core smoothing reactors. The frequency of the discharge is in the order of 300–900 Hz and the duration is typically tens of milliseconds. The objective of test can be best met by using separate high-voltage, high-power capacitor bank(s) such as those used for synthetic testing of circuit breakers. In performing the test, care must be taken to ensure that precharging of the capacitor bank(s) is such that voltage seen by the smoothing reactor under test does not exceed the switching surge level. The front time of the applied voltage should be consistent with a switching surge and care taken to ensure voltage overshoot is minimized. Consideration can be given to performing this test under wet conditions. Since dc systems vary considerably, details of this *other* test must be developed by the purchaser and manufacturer.

12.10 DC power test for oil-immersed and dry-type SMRs

The dc power test demonstrates the ability to withstand in-service steady-state operating conditions and is a quality verification, especially as a method to detect open circuited winding conductors. In case of a broken strand, intense arcing will occur across the break, similar to a dc arc welding process. In addition, the dc current will heat up the windings and the resultant thermal stresses (strain) can accentuate incipient conductor insulation damage. For dry-type air-core smoothing reactors, the test consists of loading the winding with 1.2 times rated dc current for a half-hour period and carefully observing the winding of the reactor for unusual noise, sparking, or smoke. For oil-immersed smoothing reactors, the test duration is 2 h and is part of the oil-filtration process that is carried out prior to dielectric tests. Therefore, this is an *other* test for dry-type air-core smoothing reactors and a *routine test* for oil-immersed smoothing reactors.

The dc power test is no substitute for in-process testing (continuity, hipot) that can better detect conductor damage or breaks. The test should be carried out prior to dielectric tests. Test acceptance criteria for dry-type SMRs shall be Q-factor measurement before and after, and physical observations such as no smoke or noise. For oil SMRs, Q-factor measurement before and after may be applicable, but gas and oil analysis at the end of the test should provide the best indication.

12.11 Seismic verification test

When specified, a seismic verification test shall be made on oil-immersed and dry-type air-core smoothing reactors according to IEEE Std 693-1997.

12.12 Nameplates for oil-immersed and dry-type smoothing reactors

12.12.1 Nameplate location

For oil-immersed smoothing reactors, the nameplate shall be located on the control cabinet door. For dry-type air-core smoothing reactors, the nameplate shall be located on the bottom (lower) spider.

12.12.2 Nameplate construction

A durable metal nameplate shall be affixed to each smoothing reactor by the manufacturer. Unless otherwise specified, it shall be made of corrosion-resistant material.

12.12.3 Nameplate information for oil-immersed smoothing reactors

Unless otherwise specified, the minimum information shown on the nameplate shall be that specified as follows.

- Reference to this standard
- Customer identification number
- Rated dc system voltage
- Rated current
- Thermal short-circuit current rating (magnitude and duration)
- Mechanical peak short-circuit
- Current rating
- Serial number (see Note 1)*
- Year of manufacture
- Cooling class (ONAN, ONAF, OFAF, etc.)
- Temperature rise (°C)
- Rated inductance
- Measured inductance
- Continuous current (see Note 2)
- Voltage (see Note 3)
- Basic lightning impulse insulation levels (BIL) (see Note 4)
- Approximate masses in kg (pounds) (see Note 5)
- Connection diagram (see Note 6)
- Name of manufacturer
- The words *smoothing reactor*
- Tank, pressure, and liquid data (see Note 7)
- Type of insulating liquid (see Note 7) (generic name preferred)

The following information may be useful and is optional to be included on the nameplate:

- Root sum square of dc and all significant harmonic currents
- Maximum continuous current
- Maximum system voltage
- Reference reactor outline drawing number

* Numbers in parentheses refer to the notes below

NOTES:

1—The letters and numerals showing serial number and voltage ratings shall have a minimum height of 4 mm whether engraved or stamped. The height of other letters and numerals shall be optional with the manufacturer.

2—Where the class of reactor involves more than one current rating, all ratings shall be shown.

3—The voltage rating of a smoothing reactor shall be the dc system operating voltage to ground.

4—For smoothing reactors, full wave BIL in kV of line terminals shall be designated as follows:

Terminal to ground	825 BIL
Terminal to terminal	450 BIL

5—The approximate masses shall be shown as follows:

Core and coils
Tank and fittings
Liquid
Total mass
Untanking mass (heaviest piece)

6—All winding terminations shall be identified on the nameplate or the connection diagram.

A schematic plan view shall be included. This should preferably indicate orientation by locating a fixed accessory such as instruments, control cabinet, or other prominent items. All termination or connection points shall be permanently marked to agree with the schematic identification. Indications of potential transformers, potential devices, current transducers, winding temperature devices, etc., when used, shall be shown.

Polarity and location identification of current transducers shall be shown when used for metering, relaying, or line-drop compensation. Polarity need not be shown when current transducers are used for winding temperature equipment or cooling control.

Where development of windings is shown, the scallop symbol shall be used in accordance with IEEE Std 315-1975 and IEEE Std 315a-1986.

7—For oil-immersed smoothing reactors only. Provide the following tank, pressure, and liquid data.

a) Maximum operating pressures of liquid preservation system ____ kPa (lbf/in^2)positive and ___ kPa (lbf/in^2) negative.

b) Tank designed for ___ kPa (lbf/in^2) vacuum filling.

c) Liquid level below top surface of highest point of the highest manhole flange at 25 °C ___ mm (in). Liquid level changes ___ in (mm) per 10 °C change in liquid temperature. (This applies only to reactors that have a gas cushion above the liquid in the unit.)

The volume of insulating liquid in m^3 (gallons) and type shall be shown for the main tank and for each liquid-filled compartment.

8—It is suggested that when SI units are used, that liters be used for volumes less than 1000 l, and that cubic meter be used for volumes 1000 liters and larger.

12.12.4 Nameplate information for dry-type air-core smoothing reactors

The following information must be included on the nameplate:

- *Smoothing reactor*
- Reference to this standard
- Manufacturers name
- Manufacturers serial number
- Customer identification number
- Year of manufacture
- Rated system voltage
- Basic impulse level
- Rated current
- Rated inductance
- Measured inductance
- Thermal short-circuit current rating (magnitude and duration)
- Mechanical peak short-circuit current rating
- Temperature rise
- Type of cooling
- Thermal class of insulation
- Total weight
- Altitude

The following information may be useful and is optional to be included on the nameplate:

- Root sum squared of dc and all significant harmonic currents
- Maximum continuous current
- Maximum system voltage
- Reference reactor outline drawing number

NOTE—Notes 1–4 in 12.12.3 are applicable to dry-type air-core smoothing reactors.

Annex A

(informative)

Application of HVDC smoothing reactors

A.1 Background

To date, the vast majority of HVDC links employ 12-pulse, two-bridge, line commutated (sometimes also referred to as *naturally commutated*) converters. At the sending end, the ac is converted by a converter to dc, which is reconverted at the receiving end by a second converter (inverter) to ac. For several technical reasons, which are briefly outlined in the following paragraphs, the intermediate dc circuit (dc overhead line, dc submarine cable, or the connecting bus of a back-to-back dc link) of a line commutated power converter system usually contains a smoothing reactor.

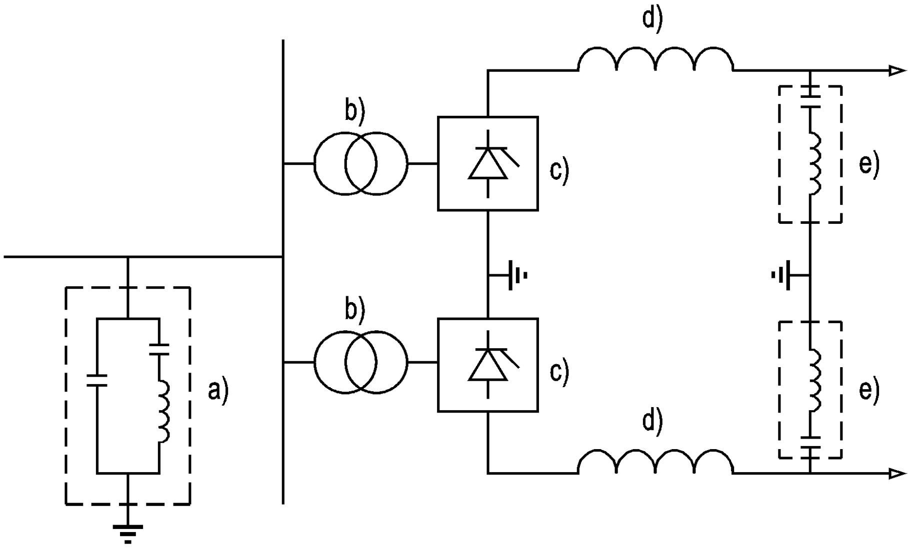
The components of converter stations may be categorized in five major subsystems. Progressing from the ac to the dc side, these subsystems are: ac filters (to attenuate harmonic currents and to provide reactive power), converter transformers, converter bridges, smoothing reactors, and dc filters. Figure A.1 illustrates, by means of one-line diagrams, the basic elements of a converter station for monopolar and bipolar HVDC transmission links as well as a back-to-back HVDC converter station.

a) AC filter/reactive power compensation
b) Converter transformer
c) Converter bridge
d) Smoothing reactor
e) DC filter

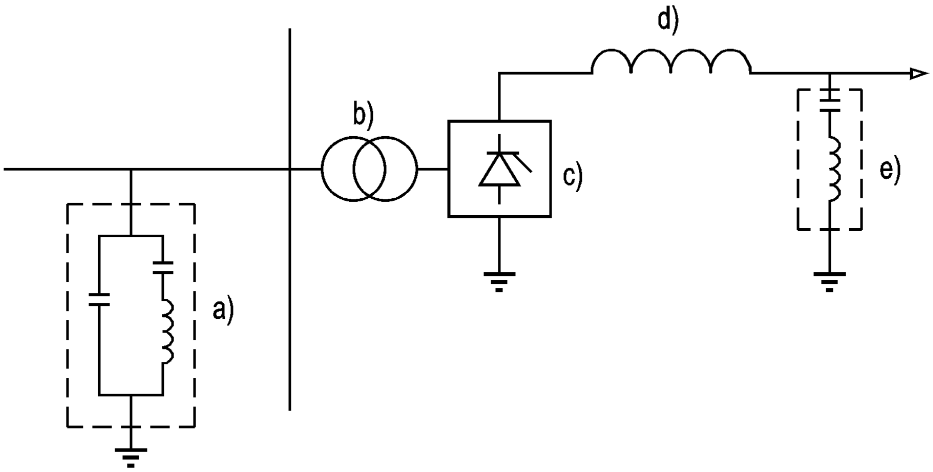
The transmission capability of an HVDC link is defined by its rated dc system voltage and the continuous dc current, which is usually about 10% higher than the rated dc current of the link. In addition, it is a general practice to require about 20% overcurrent capability above rated current for limited duration (1–2 h). The smoothing reactor must be designed to meet these loading requirements.

The inductance of the smoothing reactor of a dc line or cable is governed by system requirements such as control and stability criteria, transient overvoltage, and overcurrent protection duty for the valves.

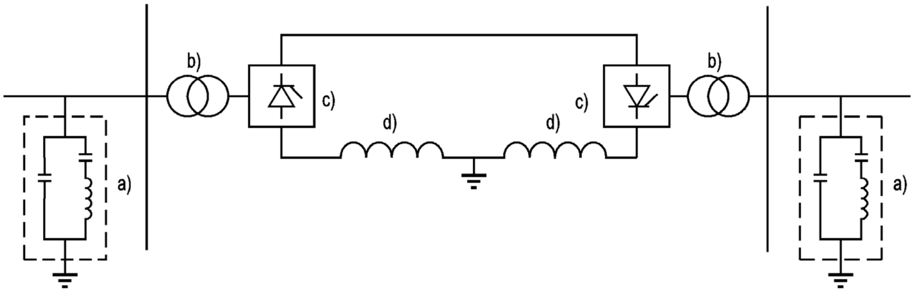
Smoothing reactors for dc links with overhead lines are an integral part of the dc filtering system and, as such, one of the main objectives is to ensure telephone interference (TIF) requirements are met. In the case of cable links, the main objective of inserting a reactor is to provide a high impedance between the converter and the capacitance of the cable, so as to limit the inrush current from the converter into the cable and to lower the flow of harmonics. In either case, the inductance must be chosen so that the reactor does not resonate with the cable or line capacitance at the ac system frequency or at multiples thereof. Additionally, if there is a railway system nearby, then multiples of the railway power system frequency must not coincide with the resonant frequency of the smoothing reactor inductance and cable capacitance.



(i) Converter station for bipolar HVDC Transmission



(ii) Converter station for monopolar HVDC transmission



(iii) HVDC back-to-back converter station

Figure A.1—One-line diagrams for HVDC converter stations

In summary, a smoothing reactor is connected in series with an HVDC transmission link or inserted in the intermediate dc circuit of a back-to-back link, for the purpose of

- Reducing the ripple in the dc current and preventing the current from becoming discontinuous during light loading.
- Preventing commutation failure of the inverter by limiting the rate-of-rise of current during commutation in one bridge (the transfer of current from one valve to another in the same row, in the bridge) and during collapse of voltage in another bridge.
- Limiting commutation failure during ac system voltage drops.
- Reducing, in conjunction with the dc filters, harmonics in the dc overhead lines to comply with TIF requirements.
- Providing a high impedance to the flow of harmonics in HVDC schemes utilizing a cable link.
- Reducing the rate of rise of current when failures occur on the dc system.
- Improving the dynamic stability of the transmission system.
- Limiting the current from the capacitive discharge of terminal equipment and the transmission line during bypass conditions in the inverter bridge.

A.2 Insulation coordination

A CIGRÉ document prepared by WG 33.05 [B2] provides some of the best background information available on insulation coordination. However, the following subclauses present important insulation coordination criteria.

A.2.1 Limiting conditions which define voltage stress across a smoothing reactor

One specific normal operating condition that significantly impacts the insulation coordination for a smoothing reactor is related to the fact that smoothing reactors are located at high dc voltage potential and have circuit elements on both sides which, at least during time intervals in the transient region, can act as constant dc voltage sources. Therefore, during a transient overvoltage event, one terminal of the smoothing reactor will be held at normal, prefault dc voltage potential, while the other is exposed to the transient, as defined by the voltage to earth. When a transient overvoltage of opposite polarity to the prefault dc voltage of the line is introduced at one terminal of the reactor, the voltage stress across the smoothing reactor will be higher than the voltage stress terminal-to-ground. Therefore, a worst case voltage stress across the smoothing reactor winding insulation system occurs when the highest transient voltage of opposite polarity is applied.

In the case of lightning, a lightning stroke may also be of opposite polarity. The amplitude will be limited by the arresters. For smoothing reactor design purposes, the lightning surge across a smoothing reactor winding is considered to be the prefault dc voltage plus lightning impulse protection level, under the assumption that there is no arrester across the smoothing reactor. This is a conservative and a worst-case scenario as normally the dc filter reduces lightning surges. However, during emergency situations the dc filter may be out of operation.

The worst switching stress across a smoothing reactor is a bit more complicated to determine, and depends on the actual system configuration. As an example, consider the configuration of a rectifier and its smoothing reactor, but without dc filter, connected to an overhead dc line. The overhead line ends at a dc cable, which completes the circuit to the inverter. During normal operation at U_{dn}, a flashover to ground occurs at the cable terminal at the inverter end. This will result in a travelling wave, with amplitude $-U_{dn}$, in the cable. When the wave reaches the overhead line, which has a much higher surge impedance, a reflection determined by the open ended line capacitance will occur. This results in a travelling wave with amplitude $-2U_{dn}$ on the overhead line. The smoothing reactor at the rectifier end of the line has a much higher impedance than the overhead line at the frequency of interest. Therefore, an additional reflection determined by open ended line conditions occurs across the smoothing reactor and is of potential magnitude $-4U_{dn}$. However, the arresters will limit the amplitude and the resulting switching surge will have an amplitude, U_{dn}, plus the switching impulse protective level. The switching surge will also be damped, so it will have a slower front than a lightning surge. A rectifier or an inverter can reverse voltage quickly during disturbances such as commutation failures and faults. Consequently, there is the possibility to inject a surge of two times the dc voltage of opposite polarity into the dc system, although it is very seldom of the full potential amplitude. In addition, overshoots have to be considered. This preceding is the background for the high switching impulse insulation level specified across a smoothing reactor.

A.2.2 Frequent operating conditions that define voltage stress across a smoothing reactor

Some of the more frequent operating conditions which define the transient voltage stress across a smoothing reactor include the following:

- During a ground fault at the rectifier, the voltage stress across the smoothing reactor will rapidly rise to the prefault dc voltage, plus some overshoot. The rise time is on the order of 1.5 µs. The duration of the dc voltage component will be several ms since the voltage is defined by the rectifier operating mode which follows a half sine wave to a voltage of opposite polarity to inverter operation for the purpose of extinguishing the fault current. This results in a dc voltage across the smoothing reactor of opposite polarity and of duration of about 10 ms until the dc current is extinguished.
- During an emergency stop, the rectifier is immediately forced to inverter operation. As the dc line capacitance is charged to the prefault voltage, the voltage across the smoothing reactor will be about twice the prefault dc voltage. The rise time is 5–7 ms and the duration is 10–15 ms.
- During a commutation failure and the ensuing inverter blocking, the dc line or dc cable will be discharged through the smoothing reactor. The voltage stress across the reactor will rise within a few microseconds to the prefault dc voltage. The voltage will then follow a sine wave to the prefault dc voltage of the opposite polarity. The oscillation frequency may be as low as 10 Hz in schemes with a long dc cable.

A.2.3 Arrester arrangement

One way to reduce the voltage stress across a smoothing reactor is to install an arrester across the smoothing reactor. However, this arrester may fail and produce a short circuit across the smoothing reactor during a transient or fault, under the very conditions when the reactor is needed for limiting the surge current. Thus, insulation coordination includes many considerations, and the design outcome depends on the total system configuration. Therefore, different philosophies may be applied for different schemes depending on system configuration and other conditions. Therefore, the purchaser shall specify relevant insulation levels for the smoothing reactor.

With regard to fast transients, experience has shown that the voltage fronts associated with flashovers of air gap spacings used for high-voltage equipment have rise times that are on the order of the front time of the standard lightning impulse. However, flashovers in SF_6 have a much steeper front. Therefore, smoothing reactors connected to equipment utilizing SF_6 insulation to ground may be exposed to very fast voltage transients and it is recommended that a chopped-wave test be specified as a routine test for such smoothing reactors.

A.3 Pollution considerations

Pollution can affect the dielectric performance of the bushings used with oil-immersed smoothing reactors and the support insulators of dry-type air-core smoothing reactors. The definition of pollution levels and associated testing methodology for insulators and bushings is evolving. Simulation of contamination levels is a difficult area. However, the IEEE dc bushing standard (IEEE Std C57.19.03-1996) is perhaps the most current and up-to-date document in its coverage of this issue. Table A.1, which defines pollution severity, is excerpted from this document.

Table A.1—General types of contaminated environments

Contamination level	Typical environments
Light	— Areas without industries and with low density of emission producing residential heating systems. — Areas with some industrial or residential density, but subject to frequent winds and/or precipitation. — Agricultural areas (exposure to wind-borne fertilizer spray or crop-burning residues can lead to higher contamination levels). — Mountainous areas. — These areas are not exposed to sea winds or located near the sea. — Typical measured ESDD (Equivalent Salt Deposit Density) levels are 0.03–0.08 mg/cm^2.
Medium	— Areas with industries not producing highly polluting smoke and/or average density of emission producing residential heating systems. — Areas with high industrial and/or residential density, but subject to frequent winds and/or precipitation. — Areas exposed to sea winds, but not right on the coast. — Typical measured ESDD levels are 0.08–0.25 mg/cm^2.
Heavy	— Areas with high industrial density and large city suburbs with a high density of emission producing residential heating systems. — Areas close to the sea or exposed to strong sea winds. — Typical measured ESDD levels are 0.25–0.6 mg/cm^2.
Extra heavy	— Small areas subject to industrial smoke producing thick conductive deposits. — Small coastal areas exposed to very strong and polluting sea winds. — Typical measured ESDD levels are above 0.6 mg/cm^2.

The steady state operating voltage across HVDC smoothing reactors is quite low (the voltage drop due to ripple current is typically on the order of 10–40 kV). However, the full system dc potential is seen across the bushings of oil-immersed reactors and the support insulators of air-core reactors. Therefore, where pollution levels are significant, appropriate creepage requirements for bushings and insulators should be determined.

Insulators, bushings, conducting and insulating surfaces on equipment at high dc potential (including the outer surface of air-core smoothing reactors) tend to act as electrostatic precipitators by attracting charged or polarizable particles.

Special coatings can be used to mitigate the effects of pollution build-up and shields can be employed on air-core reactors to reduce the rate and ultimate level of pollution deposition on the reactor surfaces.

A.4 Surge current stresses

The surge current waveform, to which the smoothing reactors are exposed in operation, usually consists of a single half sine wave. Typically, the frequency of the surge current is well below the 50 Hz or 60 Hz power frequency. Depending on the circuit configuration, the duration of the half sine wave surge is on the order of 15–50 ms.

The conditions producing the surge current are different for an inverter and a rectifier. The typical cause for a rectifier surge current is a pole to ground fault at the rectifier end of the dc line. The amplitude is determined by the inductance of the smoothing reactor and rectifier control. Typically, the amplitude is on the order of five times the rated dc current. The duration is also determined by rectifier control and is typically on the order of 20 ms.

A typical inverter side surge current event is the result of protective blocking of the inverter. This involves the firing of a bypass-pair, which acts as a diode. The dc line is then discharged through the bypass-pair of the blocked inverter and the smoothing reactor. In the case of a dc cable, the capacitance of the dc line may be significant. The prefault dc voltage, the inductance of the smoothing reactors, and the dc line/cable capacitance determine the surge current amplitude. This surge current is superimposed on the prefault dc current. In addition, there will also be an overshoot produced by the rectifier. As a result of the diode characteristic of the bypass-pair, there will be only one single surge, which will charge the dc line to the opposite polarity. In schemes with a dc cable, this case is normally more severe than a rectifier side dc line-to-ground fault.

Inverter side ac network disturbances may cause commutation failures. Temporarily, a bypass-pair is formed producing a current surge similar to that for an inverter blocking. However, supported by control actions, the inverter will recover and resume normal operation after the discharge of the dc line.

Surge currents of much longer duration may result if a fault is combined with protection interaction and/or control malfunction. If the rectifier is blocked by a fired bypassed-pair due to a protection action, as a result of the overcurrent due to a dc line-to-ground fault, the surge current decay time will typically be about 1 s. The magnetic field of the smoothing reactor, which will be at a value established by the maximum surge current, will collapse and result in a discharge current through the ground fault, the converter neutral side ground connection, and the bypassed-pair. There will be no reactive current limitation, only damping provided by losses. A typical all-encompassing case for a rectifier surge current is the combination of ground fault and control malfunction, leading to an overcurrent protection trip. This conservative scenario will result in a combination of high magnitude surge current with a long decay time. Typically the surge amplitude is ten times rated dc current and the decay time is about 1 s.

Inverter side blocking may also lead to surge currents with a long decay time, if at the same time, the rectifier is blocked due to protection interaction.

Annex B

(informative)

Construction and installation of dry-type air-core smoothing reactors for HVDC application

B.1 General description

Dry-type air-core smoothing reactors, as the descriptor implies, employ a solid insulation system as opposed to liquid-based insulation systems such as an oil- and Kraft-paper system. The main feature of this design approach is that the windings are at line potential, and the major insulation to ground is supplied by the supporting insulators. Windings are normally groups of fully encapsulated concentric annuli separated by vertical cooling ducts to provide cooling by natural convective air flow. The live encapsulated windings are directly exposed to the environment and thus, care must be taken in selecting encapsulation materials and coatings.

B.2 Transportation

The location of many HVDC projects has resulted in long and difficult transport for the equipment. The transport of very large heavy power equipment is a particular challenge and dry-type air-core SMRs are not an exception. Special braced crate designs with built-in inspection points and shock absorbing capability have been developed to minimize stresses in critical components (insulation system, winding end mechanical fixation, and tie systems) during transport. Special lifting systems have also been developed, especially for large smoothing reactors. These include multipoint lifts using special shackles or beam structures. The structural integrity of the SMR itself has been improved, based on experience.

B.3 Concrete foundation

Since dry-type air-core smoothing reactors employ a solid insulation system, they can be mounted directly on a concrete pad-type of foundation; no containment system is necessary. As a general rule of thumb, the mass of the concrete foundation should be two to three times the mass of the unit.

Dry-type air-core smoothing reactors used on HVDC transmission projects are mounted on insulators rated for the full system voltage, BIL, and creepage requirements. Because of the large voltage clearance provided by the supporting insulators, reinforcement in the foundation can be treated in a normal fashion and no special precautions are usually necessary. Additional information on clearance considerations can be found in B.6. In summary, the concrete foundation can be fabricated using standard civil engineering practice.

Dry-type air-core smoothing reactors used as part of an HVDC back-to-back scheme are usually located at the neutral and hence, support insulator or dielectric requirements are based on system operating conditions only. Therefore, clearance provided to the foundation may not be sufficient to maintain eddy losses in foundation reinforcement at safe levels. Additional magnetic clearance may have to be provided as part of the reactor support structure and/or precautions taken in the foundation design. Fiberglass reinforcement bars are now readily available and have been used successfully. Support structure clearances do not have to be increased and this is a particular advantage in seismic zones.

B.4 Safety

Since the major insulation to ground is provided by the support insulators, they are at live potential. Typically, personnel clearance can be provided by either mounting the insulators on a grounded structure of sufficient height, or more simply, by providing a fence around the area in which the smoothing reactor(s) is located.

B.5 Installation

Smoothing reactors for HVDC application are classified as heavy electrical equipment. Dry-type air-core smoothing reactors for HVDC application are typically 25 000–50 000 kg in weight. Consequently, it is imperative that lifting instructions be followed explicitly. Due to the high weight, a 4-point lift is usually the recommended method of lifting the unit into position. Therefore, dry-type air-core smoothing reactors are designed to facilitate lifting and are usually supplied with lifting eyes to facilitate rapid installation and replacement.

In general terms, verification at the site of the integrity of a newly delivered unit can be best achieved through a detailed visual inspection per the manufacturer’s instructions. This could include checks for damage to the crate, the unit itself, impact recorder readings if utilized, etc.

Since dry-type air-core smoothing reactors are cooled by natural air convection and as a consequence of their large power rating, there are a large number of cooling ducts. As part of the visual inspection that should be carried out after installation, a key area to focus on is to ensure that nothing has become lodged in a cooling duct that could either block air flow or create a dielectric problem.

B.6 Magnetic clearances

Magnetic clearances can be an important consideration for ac reactors due to the induced heating effects that may occur because of the alternating magnetic field. In the case of smoothing reactors, the largest magnetic field component is static, and it is only the ripple current that creates an alternating magnetic field. If this is quite small, then induced heating effects in nearby metallic objects are significantly reduced. The other factor that mitigates any ripple-current-based induced heating effects is the height of the unit above ground, which is necessitated by the system voltage requirements. This is especially true in the case of dry-type air-core smoothing reactors used as part of a HVDC transmission system. In the case of dry-type air-core smoothing reactors used in HVDC back-to-back schemes, the required voltage clearance to ground and to adjacent metallic geometries may not be adequate for magnetic clearance purposes. For instance, if chain link fencing is used, care should be taken. A double-post system can be used to break the fence into isolated sections. However, if temperatures are still too high, plastic fencing may have to be used.

B.7 Corona protection

Dry-type air-core reactors utilized for HVDC application are installed at high potential above ground and, therefore, it is critical to ensure that supplied corona protection is installed correctly. This corona protection is utilized not only to meet RIV requirements, but may also be part of the transient voltage design of the end electrode geometry. Failure to install corona protection properly during installation can lead to corona discharge and, if a transient overvoltage were to occur under such a condition, a possible flashover might occur.

B.8 Installed sound level

The sound level produced by a smoothing reactor is highly dependent on the magnitude of the ripple current. The dc current in the winding creates a strong static magnetic field (similar to that produced by dc magnets in a loud speaker) and the ripple current interacts with this static dc field to induce vibration in the windings and hence, sound. Therefore, the total sound emanating from a smoothing reactor is basically a function of the magnitude of the ripple current.

In some cases where stringent sound level requirements exist, dry-type air-core smoothing reactors may be supplied with a sound screen to provide further mitigation of sound. A sound screen may or may not be an integral part of the reactor and may have to be taken into consideration during the installation of the unit.

B.9 Protection practices

In most HVDC installations, lightning arresters (LA) are used to provide auxiliary protection for equipment. Smoothing reactors are no exception. In the case of dry-type air-core smoothing reactors, lightning arresters have been either mounted directly to the reactor using auxiliary support elements or mounted near the reactor on a separate support structure. The latter method is preferable in areas of significant seismic activity as a directly mounted LA will result in asymmetric loading under seismic conditions.

B.10 Connection

Most smoothing reactors for high-voltage dc application are high-current devices. Since most of the current is dc, eddy current losses are not usually a concern. Therefore, the primary focus of the connection is to provide a good high-current connection and, therefore, practices commensurate with such a connection should be utilized. In addition, due to the high dc voltage potential, corona screening of the connections should be considered.

Annex C

(informative)

Short-circuit capability

C.1 Introduction

At the time of writing of this standard, and based on inputs from major test labs, indications are that required (specified) short-circuit peak currents may not be achievable for high inductance SMR.

C.2 Overview of short-circuit testing capabilities

C.2.1 Traditional power frequency short-circuit test

A brief synopsis of power frequency short-circuit testing capabilities will provide guidance as to when an actual meaningful test can be carried out.

For power frequency short-circuit tests on coils, the high power laboratory may be supplied either by the network or by short-circuit generators. At the time of writing of this standard, the maximum short-circuit power of the most powerful labs worldwide is around 8000 MVA 3∅.

Maximum short-circuit power transfer into the coil is achieved when its impedance is equal to the impedance of the source. Then the source power required to make a short-circuit test is 4 times the power taken by the coil. For single-phase tests, the maximum source power is 2/3 of the 3∅ power. Thus, assuming a generating short-circuit power of 8000 MVA the maximum test power for a single-phase coil is about 1250 MVA.

If, for example, a single-phase 150 mH coil is tested at 50 Hz and the laboratory has no voltage limitation, the maximum symmetrical short-circuit current is 5.2 kA (243 kV rms across the coil). Assuming a crest factor of 2.7 for a completely off-set short-circuit test, the achievable peak current is 14.2 kA. The test duration might be a half cycle.

It seems meaningful to perform a short-circuit test, as an *other* (design) test, for single-phase coils having a rated short-circuit power less than about 1500 MVA. For coils having a higher rated short-circuit capability, calculations should be provided.

C.2.2 Simulation of in-service fault current

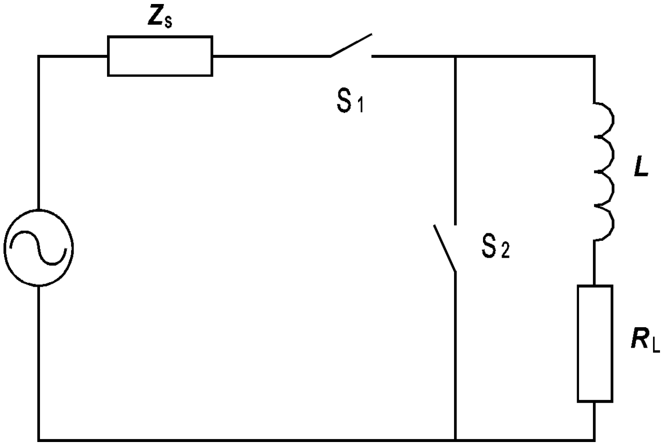
Another alternative to performing a traditional power frequency short-circuit test is to utilize test circuitry that will more closely produce the long duration fault wave shape that may be seen by HVDC smoothing reactors in service.

The inductance of HVDC smoothing reactors typically ranges from 100 mH to 500 mH and the peak value of the fault current is between 10 kA to 20 kA. The wave shape of the fault current typically has a rise time of around 10 ms and time constant for decay in the order of 1 s.

Using the circuit in Figure C.1, it is possible to simulate in-service fault currents of long decay time. The reactor is first charged through S1 and then discharged through S2, which is closed at the first peak of the current through the reactor. Thereafter, S1 is re-opened and the power supply becomes disconnected at the first or second zero of the current through S1.

The achievable peak current is the same as for a normal power frequency short-circuit test.

The time constant of the current decay depends on the resistance of the reactor and the external losses of the current measuring shunt, the shorting bar and the shorting switch S2. Typically the time constant is in the order of several hundreds of milliseconds.



Z_S is source impedance,
L is reactance of the smoothing reactor,
R_L is resistance of the smoothing reactor.

Figure C.1—Diagram of test circuit

C.2.3 Testing of partial coils

For some projects, for dc filtering or shipment considerations, the smoothing reactor may be supplied as two partial coils. If a smoothing reactor is supplied as partial coils (e.g., 2 units to make one SMR) then it may be possible to perform a short-circuit test on the partial coil at a more significant level of short circuit current since the inductance of a partial coil would be an integral fraction of the number of partial coils. In the case of dry-type air-core SMRs, there are a number of complex variables to consider. Variables include interactive force effects on support structures, coupling effects, etc.

C.2.4 Summary of short-circuit test capabilities

Table C.1 is an attempt to summarize short-circuit test capabilities vs. SMR short-circuit requirements for typical HVDC projects, i.e., over land and cable.

For long-cable projects, the operational short-circuit level will be still higher, typically: 300 mH/25 kA_{peak}, 150 mH/33 kA_{peak}. In fact, the specified short-circuit test requirements for smoothing reactors to be installed in HVDC schemes with long dc cables are typically set at even higher values in order to provide margin to ensure that there is no risk of in-service mechanical fatigue problems. The rationale is based on the experience that, for long-cable projects, the governing surge current events occur frequently, at least several times per year.

Based on Table C.1, it can be seen that for large SMRs, the performance of an actual short-circuit test may not be meaningful. Keeping in mind that short-circuit forces (stresses) are proportional to current squared.

Table C.1—Short-circuit test capabilities vs. SMR short-circuit requirements for typical HVDC project

SMR Inductance (mH)	Achievable short-circuit current (kA peak)	Specified reactor short-circuit requirements for recent projects (kA peak)
100	17.0	
200	12.0	16.0
225	11.3	
240	11.0	16.5
300	9.8	

A test at 80% of rated short circuit only produces 64% of rated mechanical stresses. This would appear to be a reasonable transition point for utilizing calculations vs performing a short-circuit test.

C.3 Calculation of short-circuit stresses in HVDC SMRs

If commercial test labs cannot achieve sufficient current levels, keeping in mind that mechanical forces are proportional to current squared, then a calculation-based method of demonstrating mechanical integrity under in-service line fault conditions may be the only viable option. For a calculation method to be meaningful, critical mechanical stress areas must be identified for both oil- and dry-type reactors and some way of relating the calculated stresses to those in a lower rated reactor that has been short-circuit tested must be agreed upon by manufacturer and purchaser. Very few oil-immersed smoothing reactors have been manufactured at a rating that enabled short-circuit tests to be performed and therefore, ac power transformers on which short-circuit tests have been performed can be used as comparators for short-circuit calculations. Similarly, in the case of dry-type air-core smoothing reactors, short-circuit tests on other reactor types (such as high-voltage series reactors) can also be used for comparison purposes. In both cases, the validity of such comparisons must be justified.

Critical stress areas will be different for oil-smoothing reactors vs. dry-type smoothing reactors. Critical stresses that are common for oil and dry-type SMRS are winding hoop and winding compression stresses. For oil-immersed SMRs, a demonstration that the winding clamping system won’t become loose under short circuit must be included. In addition, for oil-smoothing reactors, winding spiraling effect is a critical stress that must be assessed.

One additional advantage of a calculation method is that mechanical stress capability can be demonstrated before a unit is even manufactured.

Annex D

(informative)

Bibliography

[B1] Arrillaga, J., “High Voltage Direct Current Transmission,” London: Peter Peregrinous Ltd., 1983.

[B2] CIGRÉ W.G. 33.05 “Application Guide for Insulation Co-Ordination and Arrester Protection of HVDC Converter Stations,” Electra No. 96, Oct. 1984, pp. 101–156.[9]

[B3] CIGRÉ W.G. 3305, Electra No. 96, Oct. 1984, pp. 101–156, “Application Guide For Metal Oxide Arresters Without Gaps For HVDC Converter Stations.”

[B4] EPRI Report No. EL-5414, Oct. 1987, “Handbook For Insulation Co-ordination of High-Voltage DC Converter Stations.”

[B5] IEC 60071-5 (1999), Procedures for HVDC converter stations.

[B6] IEC 60919-1 (1988), Performance of high-voltage dc (HVDC) systems. Part 1: Steady-state conditions.

[B7] IEC/TR 60919-2 (1990), Performance of high-voltage dc (HVDC) systems. Part 2: Faults and switching.

[B8] IEC/TS 60919-3 (1999), Performance of high-voltage dc (HVDC) systems. Part 3: Dynamic conditions.

[B9] IEEE Std 100-1996, IEEE Standard Dictionary of Electrical and Electronics Terms, Sixth Edition.

[B10] IEEE Std 1204-1997, IEEE Guide for Planning DC Links Terminating at AC System Locations Having Low Short-Circuit Capacities, Parts I and II.

[B11] IEEE Std C57.21-1990 (Reaff 1995), IEEE Standard Requirements, Terminology, and Test Code for Shunt Reactors Rated Over 500 kVA.

[B12] IEEE Std C57.104-1991, IEEE Guide for the Interpretation of Gases Generated in Oil-Immersed Distribution Transformers.

[B13] Kimbark, E. W., *Direct Current Transmission*, Volume I, New York, Wiley—Interscience: 1971.

[B14] Lindroth, A. (CIGRÉ Joint W.G. 12/14.10 of Study Committee 12 and 14) “The Relationship Between Test and Service Stresses As A Function of Resistivity Ratio For HVDC Converter Transformers and Smoothing Reactors,” ELECTRA No. 157, December 1994, pp. 33–57.

[B15] Uhlmann, E., *Power Transmission by Direct Current*, New York, Springer-Verlag: 1975.

---

[9] CIGRÉ publications are available from CIGRÉ Central Office, 3-5 Rue de Metz, F-75015 Paris, France.