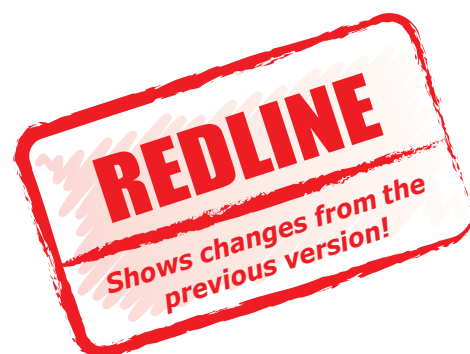


IEEE Standard for Requirements, Terminology, and Test Code for Dry-Type Air-Core Series-Connected Reactors

IEEE Power & Energy Society

Sponsored by the
Transformers Committee



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IEEE Standard for Requirements, Terminology, and Test Code for Dry-Type Air-Core Series-Connected Reactors

Sponsor

Transformers Committee
of the
IEEE Power & Energy Society

Approved 31 October 2011

IEEE-SA Standards Board

Abstract: Recommendations are given for reactors intended for series connection, in both transmission and distribution systems, to control power flow under steady-state conditions and/or limit fault current under short-circuit conditions. Dry-type air-core reactors covered by this standard are self-cooled by natural air convection. With some restrictions, other reactors, including filter reactors, shunt capacitor reactors (used with shunt capacitor banks), and discharge current-limiting reactors (used with series capacitor banks) are also covered.

Keywords: air-core reactors, discharge current-limiting reactors, dry-type air-core reactors, dry-type reactors, filter reactors, harmonic filters, IEEE C57.16, reactors, series capacitor bank applications, series-connected reactors, series reactor applications, shunt capacitor bank applications, shunt capacitor reactors

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Introduction

This introduction is not part of IEEE Std C57.16-2011, IEEE Standard for Requirements, Terminology, and Test Code for Dry-Type Air-Core Series-Connected Reactors.

The work to revise IEEE Std C57.16-1996, IEEE Standard Requirements, Terminology, and Test Code for Dry-Type Air-Core Series-Connected Reactors, was carried out by the Dry-Type Reactor Working Group, reporting to the Dry-Type Transformers Subcommittee of the IEEE Transformers Committee. Several important objectives for the revision led to the current document:

- a) Test code has been updated to reflect current test equipment technology and current application considerations.
- b) An informative annex has been added to provide guidance and background information on the impact of reactors on the transient recovery voltages (TRV) seen by circuit breakers. In simple terms, one of the purposes of using a current-limiting reactor is to protect the circuit breaker from fault current beyond its short-circuit rating; however, in applying the current-limiting reactor, the TRV capability of the circuit breaker might be exceeded. One of the most common forms of mitigation is to use capacitors. These capacitors are very often in the scope of supply of the reactor manufacturer. This is the primary rationale for including Annex F in this standard. On a secondary basis, the material in the annex is included only to provide guidance and to “caution” and is not meant to “supersede” information in the referenced switchgear standards. In fact, another purpose of the annex is to direct readers to the appropriate switchgear documents.

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1. Overview

1.1 Scope

This standard applies to *series-connected* dry-type air-core single-phase and three-phase outdoor or indoor reactors of distribution and transmission voltage class that are connected in the power system to control power flow under steady-state conditions and/or *limit* fault current under short-circuit conditions. Dry-type air-core reactors covered by this standard are self-cooled by natural air convection.

With some restrictions, this standard is applicable to filter reactors, shunt capacitor reactors (used with shunt capacitor banks), and discharge current-limiting reactors (used with series capacitor banks). Annex A, Annex B, and Annex C are included to provide guidance.

This standard does not apply to devices such as

- a) Shunt reactors (see IEEE Std C57.21-1990, ~~IEEE Standard Requirements, Terminology, and Test Code for Shunt Reactors Rated Over 500 kVA~~, [TM-2008](#))¹
- b) Arc suppression coils
- c) Neutral grounding devices (see IEEE Std 32TM-1972 (~~Reaff 1990~~), ~~IEEE Standard Requirements, Terminology, and Test Procedures for Neutral Grounding Devices~~); [\[B21\]](#))²

¹[Information on references can be found in Clause 2.](#)

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²[Numbers in brackets correspond to the numbers in the bibliography in Annex G.](#)

- d) Line resonant reactors
- e) High-voltage direct current (HVDC) smoothing reactors ([IEEE Std 1277TM-2010 \[B23\]](#))
- f) Forced cooled reactors, ~~and~~
- g) Line traps and radio interference (RI) filter reactors (ANSI C93.3-1995).

1.2 Purpose

[The purpose of this standard is to define the requirements and test code for series-connected dry-type aircore reactors and, with some restrictions, filter reactors, shunt capacitor reactors, and discharge current limiting reactors.](#)

~~The existing ANSI C57.16-1958, which is still in use by the industry, is out of date and has been withdrawn as an IEEE standard. It has now been revised to reflect modern product technology, to describe up-to-date test methods, and to present application requirements for series reactors.~~

2. Normative references

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

~~This standard shall be used in conjunction with the following publications:~~

~~ANSI C29.9-1983 (Reaff 1996), American National Standard—Wet Process Porcelain Insulators (Apparatus, Post Type).¹~~

~~ANSI C37.06-1987 (Reaff 1994), American National Standard—Preferred Rating and Related Required Capabilities for AC High Voltage Circuit Breakers Rated on a Symmetrical Current Basis.~~

~~ANSI C37.12-1991, American National Standard—Specification Guide for AC High Voltage Circuit Breakers Based on a Symmetrical Current Basis.²~~

~~ANSI C84.1-1989, American National Standard—Voltage Ratings for Electric Power Systems and Equipment (60 Hz).~~

ANSI C93.3-1995, American National Standard—Requirements for Power-line Carrier Line Traps.³

ANSI S1.4-1983, American National Standard Specification for Sound Level Meters (includes supplement ANSI S1.4a-1985).

ANSI S1.11-1986 (Reaff 1993), American National Standard Specification for Octave-Band and Fractional-Octave-Band Analog and Digital Filters.

~~IEC 143-1-1992, Series capacitors for power systems—Part 1: General—Performance, testing and rating—Safety requirements—Guide for installation.~~

[IEC 60076-10:2005, Power transformers—Part 10: Determination of sound levels.](#)⁴

~~IEC 143-2 1994, Series capacitors for power systems—Part 2: Protective equipment for series capacitor banks.~~

IEEE Std 1TM-2000 ~~1986 (Reaff 1992)~~, [\(Reaff 2011\)](#), IEEE Recommended Practice—General Principles for Temperature

~~IEC 722 1982, Guide to the lightning impulse and switching impulse testing of power transformers and reactors. Appendix A, Principles for wave shape control.~~

~~IEC 943 1989, Guide for the specification of permissible temperature and temperature rise for parts of electrical equipment, in particular for terminals.~~

Limits in the Rating of Electrical Equipment and for the Evaluation of Electrical Insulation ~~(ANSI)~~,^{5,6}

IEEE Std 4TM-1995, IEEE Standard Techniques for High-Voltage Testing ~~(ANSI)~~.

[IEEE Std 693TM-2005, IEEE Recommended Practice for Seismic Design of Substations.](#) IEEE Std ~~18-1992~~ [824TM-2004](#), IEEE Standard for ~~Shunt Series Capacitor Banks in~~ Power ~~Capacitors (ANSI)~~ [Systems](#).

~~IEEE Std 100 1996, IEEE Standard Dictionary of Electrical and Electronics Terms.~~

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

[IEEE Std C57.21TM-2008, IEEE Standard Requirements, Terminology, and Test Code for Shunt Reactors Rated Over 500 kVA.](#)

[IEEE Std C57.98TM-1993 \(Reaff 1999\), IEEE Guide for Transformer Impulse Tests. NEMA CC 1-2009, Electric Power Connection for Substations.](#)⁷

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~~IEEE Std 693-1984 (Reaff 1991), IEEE Recommended Practices for Seismic Design of Substations (ANSI).~~

~~IEEE Std 824-1994, IEEE Standard for Series Capacitors in Power Systems (ANSI).~~

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

~~IEEE Std C57.12.90-1993, IEEE Test Code for Liquid-Immersed Distribution, Power and Regulating Transformers and IEEE Guide for Short-Circuit Testing of Distribution and Power Transformers (ANSI).~~

~~IEEE Std C57.21-1990 (Reaff 1995), IEEE Standard Requirements, Terminology and Test Code For Shunt Reactors Rated Over 500 kVA (ANSI).~~

~~IEEE Std C57.98-1994, IEEE Guide for Transformer Impulse Tests (ANSI).~~

~~IEEE Std C62.1-1989 (Reaff 1994), IEEE Standard for Gapped Silicon Carbide Surge Arresters for AC Power Circuits (ANSI).~~

~~IEEE Std C62.2-1989 (Reaff 1994), IEEE Guide for the Application of Gapped Silicon Carbide Surge Arresters for Alternating Current Systems (ANSI).~~

~~IEEE Std C62.11-1993, IEEE Standard for Metal-Oxide Surge Arresters for Alternating Current Power Circuits (ANSI).~~

~~IEEE Std C62.22-1991, IEEE Guide for the Application of Metal Oxide Surge Arresters for Alternating Current Systems (ANSI).~~

~~NEMA 107-1988 (Reaff 1993), Methods of Measurement of Radio Influence Voltage (RIV) of High Voltage Apparatus.⁵~~

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3. Definitions

~~All definitions, except as specifically covered in this standard, shall be in accordance with IEEE Std 100-1996. For the convenience of the user, definitions are organized by category.~~

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary: Glossary of Terms & Definitions*⁵ should be referenced for terms not defined in this clause.

3.1 Types of dry-type air-core series reactors

air-core reactor: A reactor that does not include a magnetic core or magnetic shield.

indoor reactor: A reactor that, because of its construction, shall be protected from the weather.

outdoor reactor: A reactor of weatherproof construction.

three-phase dry-type air-core reactor: A reactor made up of single-phase devices that are stacked and magnetically coupled. Depending on the application, the self-inductance may be modified to compensate for mutual coupling effects.

~~⁵NEMA publications are available from the National Electrical Manufacturers Association, 1300 N. 17th St., Ste. 1847, Rosslyn, VA 22209, USA.~~

3.2 Series reactor applications

bus tie reactor: A current-limiting reactor for connection between two different buses or two sections of the same bus for the purpose of limiting and localizing the disturbance due to a fault in either bus.

current-limiting reactor: A reactor connected in series with the phase conductors for limiting the current that can flow in a circuit under short-circuit conditions⁷, or under other operating conditions, such as capacitor switching, motor starting, synchronizing, arc stabilization, etc.

duplex current-limiting reactor: A center-tapped reactor used in two circuit branches fed by a common circuit and wound ~~in such a way as to employ~~ so that negative coupling is employed under normal operating conditions to reduce circuit impedance and positive coupling is employed under fault conditions to increase circuit impedance.

feeder reactor: A current-limiting reactor connected in series with a feeder circuit, for the purpose of limiting and localizing the disturbance due to faults on the feeder.

high-voltage power flow control reactor: A transmission class reactor connected in series with the transmission system in order to optimize power flow by altering the line reactance.

insertion reactor: A reactor that is connected momentarily across the open contacts of a circuit interrupting device for synchronizing and/or switching transient suppression purposes.

load balancing reactor: A series-connected reactor used to correct the division of current between parallel-connected transformers or circuits that have unequal impedance voltages under steady-state and short-circuit conditions.

motor starting reactor: A current-limiting reactor used to limit the starting current of a machine.

NOTE—Various technical publications are available that cover the application of series reactors and can be consulted to provide more background information, application considerations, case studies, etc.⁹

⁸The IEEE Standards Dictionary: Glossary of Terms and Definitions is available at <http://shop.ieee.org>.

⁹Notes in text, tables, and figures in a standard are given for information only and do not contain requirements needed to implement the standard.

3.3 Rating

rating of a series reactor: The current that a series reactor can carry at its specified reactance together with any other defining characteristics, such as system voltage, basic impulse insulation level (BIL), short-circuit current (thermal and mechanical) duty, and frequency.

3.4 Current

~~3.4.1 continuous current: The maximum constant root-mean-square (rms) power-frequency current that can be carried continuously without causing further measurable increase in temperature rise under prescribed conditions of test, and within the limitations of established standards.~~

mechanical short-circuit rating: The maximum asymmetrical (peak) fault current that the reactor is capable of withstanding with no loss of electrical or mechanical integrity.

rated continuous current: The maximum root-mean-square (rms) power-frequency current ~~in amperes that can be carried for a specified duty that can be continuous, or short time, or intermittent, at rated frequency without exceeding the specified temperature limits, and within the limitations of established standards.~~

rated short-time overcurrent: The root-mean-square (rms) power-frequency current, of magnitude greater than the continuous current rating, that can be carried for a specified period of time. ~~and, depending on the ambient temperature, that may result in defined loss of the reactor's service life.~~

thermal short-circuit rating: The maximum steady-state short-circuit root-mean-square (rms) current that can be carried for a specified time, the reactor being approximately at rated temperature rise and maximum ambient at the time the load is applied without exceeding the specified temperature limits and within the limitations of established standards.

3.5 Duty

continuous duty: A requirement of service that demands operation at a substantially constant current for an extended period of time.

duty: A requirement of service that defines the degree of regularity of the current through the reactor.

intermittent duty: A requirement of service that demands operation for alternate periods of current loading and rest, such alternate intervals being definitely specified.

periodic duty: A type of intermittent duty in which the current loading conditions are regularly recurrent.

short-time duty: A requirement of service that demands operation at a substantially constant current for a short and definitely specified time.

varying duty: A requirement of service that demands operation at intermittent current loading; and for periods of time, both of which may be subject to wide variation.

3.6 Voltage

nominal voltage (of a system): A nominal value assigned to a system or circuit of a given voltage class for the purpose of convenient designation.

NOTE—The term *nominal voltage* designates the line-to-line voltage, as distinguished from the *line-to-neutral* voltage. It applies to all parts of the system or circuit.

rated system voltage: The voltage of a series reactor to which operational and performance characteristics are referred. It corresponds to the nominal line-to-line or phase-to-phase system voltage of the circuit on which the reactor is intended to be used.

voltage to ground: The voltage between any live conductor of a circuit and the earth.

NOTE—Where safety considerations are involved, the voltage to ground that may occur in an ungrounded circuit is usually the highest voltage normally existing between the conductors of the circuit, but in special circumstances higher voltages may occur.

3.7 Losses and impedance at system frequency

3.7.1 Losses

3.7.1.1 “effective “equivalent” resistance: The value of resistance of a series reactor obtained by dividing the total losses, ~~as defined in 3.7.1.2 losses, items a), b), and c),~~ by the current squared at power frequency. ~~Synonym: ac resistance~~

[See: losses.](#)

losses: ~~These~~ The losses that are incident to the carrying of current. They include

- a) The resistance and eddy-current loss in the winding due to load current.
- b) Losses caused by circulating current in parallel windings.
- c) Stray losses caused by magnetic flux in other metallic parts of the reactor, in the reactor support structure, and in the reactor enclosure when the support structure and the enclosure are supplied as an integral part of the reactor installation.

NOTE 1—The losses produced by magnetic flux in adjacent apparatus or material not an integral part of the reactor or its enclosure (if supplied) are not included.

NOTE 2—For three-phase stacked reactors, the losses are those of each individual single-phase reactor and not the average value or total value of the three-phase reactors with three-phase excitation.

3.7.2 Impedance

impedance: The phasor sum of the reactance and effective resistance, expressed in ohms.

impedance voltage drop: The product of the rated ~~ohms~~²-impedance and the rated current of a series reactor.

per-unit reactance: On a rated current base, a dimensionless quantity obtained by referencing the magnitude of the reactance to the rated system line-to-neutral voltage divided by the rated current of the reactor.

NOTE—Per-unit reactance can also be defined on an arbitrary megavoltampere (MVA) base.

rated inductance: The total installed inductance at a specified frequency. It may consist of mutual as well as self-inductance components.

rated reactance: The product of rated inductance and rated angular frequency that provides the required reduction in fault current or other desired modification to power circuit characteristics.

reactance: The product of the inductance, in henries, and the angular frequency of the system.

reactance voltage drop: The component of voltage drop in quadrature with the current.

resistance voltage drop: The component of voltage drop in phase with the current.

NOTE—If the coupling is high in a three-phase stacked reactor, the resistive voltage drop and reactive voltage drop of one reactor may be significantly affected by the adjacent reactor.

4. General requirements

4.1 Service conditions

4.1.1 Usual service conditions

Series reactors conforming to this standard shall be suitable for operation at standard rating provided that the site-related conditions in the following subclauses are met.

4.1.1.1 Ambient temperature

Ambient temperature is the temperature of the air surrounding the reactor. For the purposes of this standard, it is assumed that the temperature of the cooling air (ambient temperature) does not exceed 40 °C and the average temperature of the cooling air for any 24 h period does not exceed 30 °C.¹⁰

4.1.1.2 Environmental and application-related service conditions

Reactors for outdoor application shall be designed for conditions such as rain, freezing rain (ice), snow, fog and ultraviolet (UV) ray exposure. The purchaser should, in the specification, attempt to quantify or qualify environmental conditions, including type and level of pollution. The reactor should also be designed to withstand, without damage or loss of service life, mechanical loads such as electromagnetic forces during short circuits, wind loading, and stresses caused by thermal expansion and contraction due to ambient temperature and current loading variations. Wind speed data, including gust factors, should be specified by the purchaser. In the case of indoor application, the purchaser should specify the type and level of pollution from the environment and the indoor ambient temperature range.

4.1.1.3 Altitude

The altitude does not exceed 1000 m (3300 ft).

4.1.2 Unusual service conditions and other conditions that may affect design and application

Unusual service conditions may require that particular consideration be given to the construction or operation of the equipment, and these should be brought to the attention of those responsible for the specification, manufacture, application, and operation of the equipment. Among such unusual conditions are the following:

¹⁰ It is recommended that the average temperature of the cooling air be calculated by averaging 24 consecutive hourly readings. When the outdoor air is the cooling medium, the average of the maximum and minimum daily temperature may be used. The value that is obtained in this manner is usually slightly higher than the true daily average.

a) Application at higher ambient temperatures or at higher altitudes than specified in 4.1.1.

NOTE—Standard equipment may be applied at higher ambient temperatures, or at higher altitudes than specified, but the performance will be affected.

b) Restriction of air flow to the reactor that could affect its self-cooling by natural air convection.

c) Exposure to [foreign materials, such as](#) damaging fumes or vapors; farm fertilizers and weed sprays; excessive dust, abrasive or magnetic dust; explosive mixtures of dust or gases; steam, excessive moisture, or dripping water; salt air or spray, etc.

d) Exposure to abnormal vibration, shock, or tilting.

e) Exposure to temperatures below -40°C .

f) Exposure to unusual transportation or storage conditions.

g) Unusual space limitations.

h) Operating duty, difficult or irregular maintenance, abnormal harmonic content, unbalanced voltage, special insulation requirement, etc.

i) Unusual operating requirements, such as might result from the absence of surge-arrester protection, lack of magnetic shielding, etc.

NOTE—If a series reactor is not fully shielded magnetically, consideration should be given to its location relative to other apparatus and to metallic structures, in order to minimize heating effects of stray fields at normal current and reaction forces under short circuit. The manufacturer can evaluate the suitability of an installation if provided with details of the surrounding structure.

j) Operation of system with one phase conductor grounded.

NOTE—This should be considered as an emergency operating condition, and the duration should be limited to the time reasonably required to isolate the fault.

4.2 Insulation

4.2.1 Insulation between turns

Dry-type air-core series reactors have no magnetic core; therefore, the primary internal insulation is solely the winding turn-to-turn insulation system. In the case of open-style dry-type reactor designs, the insulation between turns is provided by air and the materials utilized to separate the turns. In the case of dry-type reactors with fully encapsulated windings, the insulation between turns is usually a solid dielectric material. The material utilized to encapsulate such a reactor is ~~primarily~~ employed, in part, to provide environmental protection and mechanical strength. In selecting appropriate materials to be utilized as turns insulation on the conductors, it is necessary to evaluate dielectric properties, mechanical properties, and multifactor aging characteristics under operating conditions. Encapsulation materials are evaluated in a similar fashion. Amount, type, and method of application of materials employed are a function of manufacturing considerations, specification requirements, service (application) requirements, and site or environmental conditions.

4.2.2 Insulation between terminals

The distance between input and output terminals, the winding length, the electrode configuration of the winding ends, and the dielectric properties of the winding surface shall be such that the reactor can withstand the steady-state operating voltages, short-time, and transient overvoltages applied between the terminals.

4.2.3 Insulation to ground and between phases

The support insulators provide the primary insulation to ground and, if applicable, between phases of a dry- type air-core series reactor. These are selected based on system voltage considerations, special transient overvoltage requirements, and site environmental conditions (e.g., pollution, altitude).

4.3 Operation at altitudes in excess of 1000 m (3300 ft)

Standard equipment may be applied in locations having an altitude in excess of 1000 m (3300 ft), but the dielectric strength of air-insulated parts and the current-carrying capacity will be reduced. For instance, the effect of decreased air density due to high altitude is to decrease the flashover voltage for a given distance. See IEEE Std ~~4-1995~~⁷ [C37.100.1-2007 \[B13\]](#) for ~~use of a correction factor with sphere gaps~~ [guidance](#).

4.3.1 Dielectric strength of air-insulated parts

The dielectric strength, at [altitudes](#) greater than 1000 m (3300 ft), of air-insulated parts of a given insulation class should be multiplied by the proper altitude correction factor, as given in Table 1, to obtain the dielectric strength at the required altitude. For example, the dielectric strength of a series reactor that depends in whole or in part upon air for its insulation decreases as the altitude increases.

Table 1—Dielectric strength correction factors for altitudes greater than 1000 m (3300 ft)

Altitude		Altitude correction factor for dielectric strength
m	ft	
1000	3300	1.00
1200	4000	0.98
1500	5000	0.95
1800	6000	0.92
2100	7000	0.89
2400	8000	0.86
2700	9000	0.83
3000	10 000	0.80
3600	12 000	0.75
4200	14 000	0.70
4500	15 000	0.67
NOTE—An altitude of 4500 m (15 000 ft) is considered a maximum for standard reactors.		

4.3.2 Operation at rated continuous current

It is recognized as good practice to use reactors of standard temperature rise at rated current at altitudes greater than 1000 m (3300 ft) provided the average temperature of the cooling air does not exceed the values in Table 2 for the respective altitudes. Standard temperature limits will not be exceeded.

Table 2—Maximum allowable 24 h average temperature of cooling air to permit a dry-type air-core series reactor to carry rated continuous current

Insulation index (°C)	Altitude (°C)			
	1000 m (3300 ft)	2000 m (6600 ft)	3000 m (9900 ft)	4000 m (13 200 ft)
105	30	27	24	21
130	30	26	22	18
155	30	24	18	12
180	30	23	16	9
220	30	22	15	7
NOTE—Recommended calculation of average temperature is described in Footnote 9 (see page 6).				

4.3.3 Operation at less than rated continuous current

It is recommended that, when reactors of standard temperature rise in standard ambient temperatures are used at altitudes greater than 1000 m (3300 ft), the current to be carried be reduced below rating by 0.3% for each 100 m (330 ft) that the altitude is above 1000 m. If this is done, the standard temperature rise will not be exceeded.

⁷~~Information about references can be found in Clause 2~~

5. Rating

5.1 Basis of rating

The rating of a series reactor shall include the following:

- a) [Rated](#) reactance (in ohms or percent)
- b) Voltage drop
- c) [Rated](#) system voltage
- d) [Rated](#) continuous current
- e) Mechanical and thermal short-circuit current
- f) Number of phases
- g) [Power](#) frequency
- h) Basic [impulse](#) insulation level (BIL)
- i) [Rated inductance](#)

5.2 System frequency

The reference system frequency for series reactors used in this standard in North America is 60 Hz.

NOTE—As this standard is used outside North America, 50 Hz may be the operating frequency. In this case, calculations should be modified accordingly.

5.3 Reactance rating

Most currently available dry-type air-core series reactors are custom designed; thus the end user should specify the exact reactance required.

5.3.1 Reactance voltage drop

The reactance voltage drop of a series reactor at its rated current is obtained by multiplying the rated reactance by the rated current.

5.4 Voltage rating

Custom-designed dry-type air-core series reactors are available for any system voltage ~~rating~~ including the standard ones listed in Table 6 (in Clause 9). The rated voltage of the series reactor should be equal to or greater than the highest expected operating voltage that will be seen by the reactor in service.

~~5.5.5 Continuous current rating~~

~~5.5.4~~ Specification of continuous current rating

~~Currently available~~ Custom-designed dry-type air-core series reactors allow the end user to specify the exact current rating required, including special duty cycles.

NOTE—If harmonic current content is significant, it should be taken into consideration in arriving at the continuous current rating of the series reactor.

5.6 Short-circuit current rating

5.6.1 Mechanical and thermal short-circuit current rating

Series (current-limiting) reactors shall have a thermal and mechanical short-circuit current rating. The thermal and mechanical short-circuit rating shall be specified by the purchaser. Typically, the short-circuit rating is determined from the calculated current when any type of fault occurs at the load side terminals with a minimum of 105% of rated system voltage present as measured at the supply side terminals of the reactor. Anticipated system voltages of greater than 105% shall be specified and accounted for, as operation of reactors at a higher system voltage than that used for the short-circuit calculation imposes a severe short-circuit duty that may be beyond the mechanical strength of the reactor. It should also be emphasized that system impedance, at the location in the system where the reactor is to be installed, should be considered in arriving at the short-circuit rating of the current-limiting reactor in order to achieve an economic design that fully meets all system

requirements. [This approach, however, may result in designs that are specific to the particular system location and are not interchangeable.](#) The mechanical short-circuit current rating is based on the worst-case assumption of a simultaneous three-phase fault and the resulting offset peak current. The degree of offset is a function of system damping. The magnitude of the thermal short-circuit current rating is obtained from system fault calculations and the duration is a function of system operating policy including number of “autorecloses” of the breaker, etc. Some useful formulas and a sample calculation follow.

Reference formulas include Equation (1) through Equation (4).

$$X_L = \frac{(V_s)^2}{MVA} \quad (1)$$

$$X_R = (V_s)^2 \left(\frac{1}{MVA_A} - \frac{1}{MVA_B} \right) \quad (2)$$

$$X_R = \frac{V_s}{\sqrt{3}} \left(\frac{1}{I_{SCA}} - \frac{1}{I_{SCB}} \right) \quad (3)$$

$$I_{SC} = \frac{MVA}{\sqrt{3} \times V_s}, \quad I_{SC} = \frac{V_s}{\sqrt{3}} \times \frac{1}{X_L} \quad (4)$$

NOTE—The equation for X_L is correct only for the special case where the system resistance R is zero. In actual systems, R is finite. However, the system resistance can be ignored if the R/X ratio is small enough. For an R/X ratio of 0.05 [or an \$X/R\$ ratio of 20](#) (about the middle of Table 8 in 10.2.2), the error is about 0.1%.

where

MVA is the three-phase symmetrical system fault level, in megavoltamperes

MVA_B is the three-phase symmetrical system fault level on the source side of a series reactor

MVA_A is the three-phase symmetrical system fault level on the load side of a series reactor

X_L is the total, per-phase, system equivalent series reactance, in ohms

X_R is the reactance of series reactor, in ohms

V_s is the system line-to-line root-mean-square (rms) voltage, in kilovolts

I_{SC} is the rms short-circuit current, in kiloamperes

I_{SCB} is the per-phase, system fault current, in kiloamperes, excluding the use of a series reactor, ~~and~~

I_{SCA} is the per-phase, system fault current, in kiloamperes, including the use of a series reactor

A sample calculation is as follows:

a) Rated system voltage is equal to 13.8 kV.

b) Fault level is equal to 100 MVA at 105% of rated system voltage. c) Reduce fault level to 50 MVA at 105% of rated system voltage.

The existing system series reactance is calculated using Equation (5).

$$X_L = \frac{(13.8 \times 1.05)^2}{100} = 2.1 \, \Omega \quad (5)$$

The total series reactance required to limit fault level to 50 MVA and accounting for a nominal operating overvoltage of 105% is calculated using Equation (6).

$$X_L = \frac{(13.8 \times 1.05)^2}{50} = 4.20 \, \Omega \quad (6)$$

Therefore, the required value of the series reactor reactance is calculated using Equation (7).

$$X_R = 4.20 - 2.1 = 2.10 \, \Omega \quad (7)$$

The symmetrical rms fault-current rating of the reactor is calculated using Equation (8).

$$I_{sc4} = \frac{(13.8 \times 1.05)}{\sqrt{3}} \times \frac{1}{4.2} = 2.0 \text{ kA} \quad (8)$$

5.6.2 Short-circuit mechanical stresses

Under short-circuit conditions, the electromagnetic forces and associated stresses in the windings and ancillary components of dry-type air-core reactors can reach values tens to hundreds of times those seen under steady-state operating conditions. Forces and stresses are proportional to the square of the magnitude of the current. Windings are subjected to simultaneous hoop and compressive forces. Input and output current-carrying bus or cable (including the terminals to which they are attached) shall withstand “vectoral” loads that vary with the spatially changing pattern of the dry-type air-core reactor’s magnetic field. The reactor’s mechanical clamping structure and support elements are exposed to direct acting forces (if they carry current) as well as reaction forces.

5.6.3 Mechanical short-circuit current rating

The mechanical short-circuit current rating shall be expressed as maximum ~~crest~~^{peak} asymmetrical amperes. The maximum peak of an asymmetrical current shall be determined by the purchaser through system knowledge and the use of Equation (9) in 10.2.2. If not specified by the purchaser, the maximum peak asymmetrical current shall be considered as 2.55 times the rms symmetrical current ($I_{pk} = 2.55 \times I_{rms}$).

[NOTE—This is consistent with IEC 60076-6:2007 \[B9\].](#)

The mechanical short-circuit current rating shall be verified by a design test and/or calculation. The method of calculation is to be agreed upon by the manufacturer and the purchaser.

5.6.4 Thermal short-circuit current rating

Series (current-limiting) reactors shall have a thermal short-circuit current rating of magnitude based on the rms symmetrical fault current as specified in 5.6.1. The duration should be specified by the purchaser and should typically take into consideration system protection practices such as breaker interrupting time, breaker autoreclose sequence, etc.

The thermal short-circuit current rating shall be expressed in rms symmetrical amperes.

Typical values for the duration of the thermal short-circuit current rating are 1 s, 2 s, or 3 s. The actual required duration should be specified by the purchaser. If not specified by the purchaser, the duration of the thermal short-circuit current shall be considered to be 3 s.

NOTE—Duration of short-circuit current can impact the cost of a current-limiting reactor; therefore, it is in the purchaser's best interest to specify a realistic value of time.

The thermal short-circuit current rating shall be verified by a design test and/or calculation. The calculation method is found in 11.7.

5.6.5 Enclosures

When reactors are used in enclosures, a number of precautions should be observed. [Such precautions include at least the following.](#) For fiberglass enclosures, large metallic auxiliary parts (e.g., ventilation screens) shall be grounded ~~so as~~ [in order](#) to avoid shorted loops that could be subject to heavy current flow and damaging forces under short-circuit conditions. Metal enclosures shall be designed using the principles of sectionalization and isolation in order to avoid overheating under steady-state operating conditions and permanent distortion, excessive temperature, or sparking under short-circuit conditions.

NOTE—The design of enclosures for use with air-core series reactors requires extensive engineering expertise and proper coordination with the reactor design. It is, therefore, recommended that the design of enclosures be left to the reactor manufacturer. Manufacture of the enclosures should also be left to the reactor manufacturer unless design details are supplied.

6. Tests

6.1 Routine, design, and other tests for series reactors

Tests for dry-type series reactors are listed in Table 3.

Table 3.—Routine, design, and other tests for dry-type series reactors

		Test classification		
		Routine	Design	Other
Resistance measurement	The dc resistance measurement shall be made on all units.	X		
Impedance measurement	The impedance measurement shall be made on all units.	X		
Total loss measurement	Total losses shall be measured on all ~~counts~~ units.	X		
Temperature rise test	This test is performed on one unit out of a number of units of the same design.		X	
Applied voltage test	The applied voltage test shall be made only on support insulators when specified.			X
Radio influence voltage (RIV) test	This test is performed for nominal system voltages 230 kV and above only when specified.			X
Turn-to-turn test	This test is performed for nominal system voltages of 34.5 kV and below.	X		

Test	When performed	Test classification		
		Routine	Design	Other
Lightning impulse test				
Nominal system voltage greater than 34.5 kV	The lightning impulse test shall be performed on all units.	X		
— Nominal system voltage at or below 34.5 kV	The lightning impulse test shall be performed only when specified.			X

Switching impulse test	The switching impulse test shall be made on the support structure (insulators) of series reactors rated 230 kV or above only when specified.			X
Chopped-wave impulse test	The chopped-wave impulse test shall be made on series reactors only when specified.			X
Audible sound test	Units shall be tested only when specified.			X
Seismic verification test	The seismic verification test shall be made on series reactors only when specified.			X
Short-circuit test	<u>One unit of a design shall be tested only when specified.</u>		X	

6.1.1 Routine tests

A routine test is a test made on each and every unit of a specific design and is primarily a verification of quality. Routine tests shall be made on all series reactors in accordance with the requirements of Table 3.

6.1.2 Design tests

A design test (also referred to as a type test) is a test carried out on a single unit of a specific design and is primarily a verification of the ability to meet in-service application requirements. Design tests shall be made on ~~all~~ series reactors in accordance with the requirements of Table 3.

6.1.3 Other tests

A test designated as “other” is a test performed on one or all units of a specific design if requested by the purchaser. ~~It is usually~~ Such a test may be requested to demonstrate conformance to special application requirements as opposed to the more general application requirements covered by design tests. When specified (as individual tests), “other” special tests, as listed in Table 3, shall be made on series reactors.

6.2 Where tests are to be made

All tests are to be made at the manufacturer's plant, a recognized independent test laboratory, or other suitable facility unless specified otherwise.

6.3 Test sequence

The listing of tests shown in Table 3 does not necessarily indicate the sequence in which the tests shall be made. All tests are defined in and shall be made in accordance with Clause 11.

6.4 Test procedures

The test procedures of this standard describe accepted methods used in making the tests and specify the tests that ~~will~~ demonstrate performance to rating. They do not preclude the use of other equivalent or more effective methods of demonstrating ratings based on agreement between manufacturer and purchaser.

7. Losses and impedance

7.1 Losses

7.1.1 Tolerance on losses

A tolerance on losses is utilized for two purposes: first, for commercial evaluation; and, second, to provide the basis of a quality check.

7.1.1.1 Tolerance on losses for commercial evaluation

As energy costs increase, losses become a more significant component of total operating cost and, as such, may be evaluated by the purchaser. Therefore, compliance to guaranteed losses may become part of the commercial contract. A tolerance on losses, e.g., to account, ~~for instance,~~ for measurement tolerances ~~etc.~~ or other considerations, may be part of the contractual agreement. Additionally, the contract may specify guarantee criteria such 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.

~~The only warning that should be stressed is that~~ From an engineering standpoint, 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 system employed are not exceeded.

7.1.1.2 Tolerance on losses as the basis of a quality check

The losses on any individual reactor unit shall not differ from the average loss of all units of the same design by more than 6%. For single-phase units, the average loss shall be calculated by using the measured losses on each individual unit. For three-phase stacked reactors, the average loss for each phase shall be calculated by using the per-phase losses measured on a three-phase basis on each individual coil of a three-phase stacked reactor. For three-phase stacked reactors, the 6% tolerance on losses applies to units of the same phase.

If any of the individual 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, including the temperature rise limits.

7.2 Impedance

7.2.1 Tolerance on impedance

Tolerances on impedance apply over a current range from zero to full short-circuit rating.

7.2.2 Impedance of a single-phase reactor

The impedance of a single-phase reactor, or of the minimum tap of a single-phase reactor having more than one impedance rating, shall not vary more than +7% or –3% from its guaranteed value. The impedance for all other connections shall not vary more than +10% or –3% from the guaranteed value.

7.2.3 Self-impedance of a three-phase reactor

The self-impedance of each phase of a three-phase reactor, or of the minimum tap of a three-phase reactor having more than one impedance rating, shall not vary more than +7% or –3% from its guaranteed value. The self-impedance for all other connections shall not vary more than +10% or –3% from the guaranteed value.

7.2.4 Voltage drop

The voltage drop across each phase of a three-phase reactor, or of the minimum tap of a three-phase reactor having more than one rated voltage drop, with balanced three-phase rated current, shall be not more than 14% above or 3% below the guaranteed value. The voltage drop for all other connections shall be not more than 16% above or 3% below the guaranteed value.

7.2.5 Compensation for mutual impedance

When three-phase reactors are specified to be compensated for mutual impedance to provide balanced three-phase voltage drops, the minimum self-impedance of any phase shall be not less than 75% of the guaranteed value. Usually power systems are designed such that single-phase short-circuit currents are lower than three-phase short-circuit currents. However, it should be recognized that single line-to-ground faults on a system with a grounded neutral may result in fault currents in the lowest self-impedance phase higher than the three-phase fault currents. If no system impedance is considered, fault currents in the lowest self-impedance phase can be as high as 1.33 times the three-phase fault currents.

NOTE—In the case of orders with multiple three-phase stacks, it is permissible to assemble only one three-phase stack and by measurement obtain the coupling factor(s). These coupling factor(s) can be used to obtain the effective inductance (mutual inductance included) per phase for the other reactors in three-phase stack configuration from single-phase self-inductance measurements.

7.3 Impedance and losses test

Since dry-type air-core reactors have no iron core, the impedance and losses may be measured at any value of current and the losses corrected to rated current. For temperature correction, refer to 11.4.2.

For three-phase stacked reactors, the loss measurement shall be performed on each individual single-phase reactor when it is energized with single-phase current.

If a wattmeter is used to determine losses, then impedance can be calculated by simultaneously measuring current and voltage and dividing the voltage by the current. Bridge methods allow the simultaneous measurement of reactance (inductance) and equivalent resistance, from which impedance and losses can be calculated.

8. Temperature rise

8.1 Considerations in establishing limits of temperature rise

8.1.1 Life of insulating materials

The life of insulating materials commonly used in dry-type series reactors depends largely upon the temperatures to which they are subjected and the duration of such temperatures.

Since the actual temperature is the sum of the ambient temperature and the winding temperature rise, it is apparent that the ambient temperature very largely influences the life of insulating materials used in dry- type series reactors.

Other factors upon which the life of insulating materials depends are as follows:

- a) Dielectric stress and associated effects
- b) Vibration or varying mechanical stress
- c) Repeated expansions and contractions
- d) Exposure to moisture, contaminants, etc.
- e) Overloading (current) of the device

8.1.2 Insulating materials

~~Currently,~~ A wide range of conductor insulating materials is available. Most materials utilized today are polymers, which tend to be available in tape form, enamels or varnishes, and extrudable format. Selection of a conductor insulation material may be a function of thermal requirements, voltage requirements, mechanical requirements, or other service considerations. Because materials can exhibit different performance capabilities under various operating conditions, individual materials or combination of materials can be used in reactors of different temperature classes depending on the end application. It is for this reason that materials are no longer defined as Class B, F, or H and are now assigned temperature indices. Each temperature index assigned to a material carries the implied descriptors of temperature, number of serviceable hours at that temperature, and end-of-life criteria. In general terms, an insulating material can be assigned more than one specific temperature index depending on the end-of-life criteria and performance characteristics desired. Therefore, because materials can exhibit different performance capabilities under various construction formats and operating conditions, the classification of a dry-type reactor as being of a particular temperature class does not imply that each individual material used in its construction is of the same thermal capability. The assignment of the temperature index of the insulation system and of the associated “hot spot” temperature rise is the responsibility of the reactor manufacturer. Only experience

or adequate acceptance tests provide a basis for defining the temperature limits for the insulation system.

8.1.3 Thermal rating of materials and systems

Individual insulation and encapsulation materials may be assigned a temperature index based on ~~maintenance of the~~ [ability to retain](#) a certain performance characteristic for a specified number of hours at a specified temperature. However, in the case of dry-type air-core series reactors, it is not the performance characteristics of the constituent materials by themselves that is of interest; it is the performance of the system. Therefore, in designing dry-type air-core reactors for appropriate service life, it is not sufficient just to know the capabilities of the constituent materials; it is the performance of the system of materials that is critical [since individual materials in a system can interact](#).

Although performance at temperature is one of the main evaluating criteria for materials, multifactor aging effects also should be considered, especially for the overall system. The assessment of what the important interactive aging mechanisms are is really in the jurisdiction of the manufacturer. Interactive aging mechanisms that might have to be considered are temperature, electrical stress, thermal shock, mechanical load cycling, and environmental criteria.

Multifactor aging studies to establish the long-term performance of insulation materials are usually carried out based on principles in IEEE Std 1-~~1986~~ [2000](#).

8.1.4 Limits of temperature rise and duty of current-limiting reactors

Because series reactors are used in series with other equipment on the power system, the current through the reactor usually varies as the connected load changes. ~~Therefore~~ [Unless there are special conditions](#), series reactors do not operate at full rated current for much of their life.

Similar series-connected equipment (i.e., power line carrier wave traps; see ANSI C93.3-1995) typically have higher allowable winding temperature rise values due to variation in duty. Conversely, shunt reactors inherently have a very high continuous duty, with their current varying only with the applied voltage. Therefore, they have lower maximum winding temperature rise limits (see IEEE Std C57.21-~~1990~~ [2008](#)) than series-connected equipment, since the winding will be at maximum design temperature rise for most of its connected lifetime.

Therefore, duty is also a major factor in arriving at the temperature rise limits in Table 4 ~~of this standard~~ [\(see 8.2.3\)](#).

8.1.5 Experience factor in establishing temperature rise limits for dry-type air-core series reactors

Although knowledge of the thermal capabilities of the constituent materials in a dry-type air-core series reactor can provide a basis for establishing the allowable temperature rise limit for the reactor, service experience is also a significant determiner. This was an important criterion in arriving at the temperature rise limits in Table 4 ~~of this standard~~ (see 8.2.3). For this reason, the average temperature rise limits and hot spot temperature rise limits in Table 4 were arrived at both from the point of view of the temperature index of the insulation system and also from the application experience (including duty) and service history obtained from the application of reactors designed to identical temperature rise limits in the previous editions of this standard (ANSI C57.16-1958 [and IEEE Std C57.16-1996](#)).

8.2 Limits of temperature rise

8.2.1 Standard limits of temperature rise

The standard limits of temperature rise of series reactors shall be as given in Table 4 (see 8.2.3). Specifically, series reactors shall be designed so that the hottest-spot conductor temperature rise above the ambient temperature when operated at rated current ~~will~~ [does](#) not exceed the values given in Table 4.

8.2.2 Enclosed reactor

When a dry-type air-core reactor is enclosed, external parts that can be touched shall not exceed a 30 °C temperature rise.

8.2.3 Temperature rise of reactor parts

The temperature rise above the ambient temperature of reactor parts in contact with the insulation or encapsulation material, when operated at rated current, shall not exceed the values given in Table 4. The temperature rise limit shall be based on the specific insulation temperature index of the insulation and encapsulation materials, whichever is in contact with the metallic part. For procedures in determining temperature rise, see 11.5.

Table 4—Limits of temperature rise for continuously rated dry-type air-core series reactors

Item	Insulation temperature index b,c (°C)	Average winding temperature rise by resistance a,d,e,f (°C)	Hottest-spot winding temperature rise a,d,f (°C)
1	105	55	85
	130	80	110
	155	100	135
	180	115	160
	220	140	200
2	Metallic parts in contact with or adjacent to the insulation shall not attain a temperature in excess of that allowed for the hottest spot of the windings adjacent to that insulation.		
3	Metallic parts other than those covered in item 2 shall not attain excessive temperature rises.		

^a Temperature rise is rise above ambient in degrees Celsius.

^b A reactor with a specified temperature rise shall have an insulation temperature index that has been proven by experience or testing.

^c The insulation temperature index in Table 4 is supplied as a reference and is based on the preferred temperature index for insulation materials as defined in IEEE Std 1-2000. It should be noted that the preferred temperature index is the lowest value in a number range (of temperatures) into which insulation materials can be placed. This results in an element of conservatism in the thermal performance of an insulation system and thus constitutes part of the experience factors in assigning temperature rise limits.

^d The above average temperature rises and hot spot temperature rises are maximum upper limits. Hottest-spot winding temperature rise limits are based on the accepted experience that series reactors are subject to significant variation in duty. The reference ambient temperature is considered to be a 20 °C annual average ambient temperature in conjunction with the capability to operate in a 40 °C maximum ambient when the 24 h average is 30 °C. Specified temperature limits may be lower due to such service considerations as high average ambient temperature conditions, prolonged exposure to high ambients, indoor versus outdoor service, high continuous duty (limited “load cycling”), and loading profile (specified overloads).

^e The average winding temperature rise limits are based on the attempt to achieve an approximate 40% differential between hot spot rise and average rise. However, it should not be construed that the difference between maximum hot spot rise and average rise is a hot spot allowance. There are so many design variables involved that it is not possible to arrive at a meaningful single value. Nevertheless, it should be stressed that the intent is that neither the average winding rise nor the hottest-spot winding rise should be exceeded. Since it is generally hot spot temperature rise that determines the life of a reactor, the manufacturer and purchaser may agree that the average temperature rise can be safely exceeded for some reactor designs provided the hot spot rise limit is respected and verified.

^f Consideration should be given to specifying reduced temperature rise limits for reactors utilized on generator lines, interties, etc. In these types of applications, equipment is usually fully loaded most of the time, as opposed to more usual applications where equipment is loaded based on varying duty (“load cycled”).

8.2.4 Temperature rise of terminals

~~The temperature rise of a dry-type air-core series reactor's terminals furnished by the reactor manufacturer for connection to the user's circuits shall, in general, not exceed 60 °C. Service experience has demonstrated the validity of this guideline. However, if appropriate, a choice of terminal plating material, contact aids, bolting technique, etc., can make higher terminal operating temperatures possible. If more information is required regarding terminal operating temperatures, surface contact preparation, electrical contact aids, plating materials, etc., then [B1], [B2], [B3], and [B6] can be consulted.~~

[Table 5 gives the temperature rise limits for terminals.](#)

[Table 5—Temperature rise limits for terminals](#)

Terminal description Connection, bolted or the equivalent	Maximum value	
	Temperature (°C)	Temperature rise at ambient air temperature not exceeding 40 °C
Bare-copper, bare-copper alloy or bare-aluminum alloy – in air	90	50
Silver-coated or nickel-coated – in air	115	75
Tin-coated – in air	105	65

[For more information, see Braunovic \[B3\], \[B4\], and \[B5\]; Jackson \[B25\]; and IEC/TR 60943:2007 \[B11\].](#)

NOTE—It should be recognized that the terminals of reactors, of necessity, come at the ends of the winding where the flux density may be almost as high as it is inside the coil. Therefore, it is important, especially for high-current reactor units, to use appropriate connectors, preferably those that present a streamlined geometry to the magnetic field. It is also critical that the dimensions and the direction of approach of the user's conductors do not increase the eddy losses; otherwise, the temperature rise of the connection may be greatly increased. If the user's conductor insulation is limited to a lower temperature rise than that allowed for the reactor terminal, a section of bare conductor that radiates sufficient heat to provide the desired temperature differential should be inserted by the user.

8.3 Temperature rise tests

8.3.1 Test methodology

This test shall be made by passing rated [continuous](#) current through the reactor until the temperature rise becomes constant and then determining the hottest-spot temperature rise, where practicable, together with the average winding temperature rise. The temperature rise tests shall be made in a room that is essentially draft-free.

When the available test power does not permit making the test at rated [continuous](#) current, then the manufacturer should demonstrate to the user that reduced current testing produces sufficiently accurate results when extrapolated to rated current level. The manufacturer should notify the user of reduced current level testing during the proposal stage.

NOTE—For higher current rated units, knowledge of in-service terminal temperature rise may be of importance. In this case, consideration should be given to performing the temperature rise test with the actual connectors to be used in service, especially if they differ from those recommended by the manufacturer. If the connectors are not supplied by the manufacturer, the end user should supply them. It is important ~~to ensure~~ that conditions for such a test truly reflect in-service operating conditions, or erroneous results may be obtained. Test conditions should be agreed to by manufacturer and end user.

8.3.2 Hottest-spot determination

The hottest-spot temperature rise for dry-type series reactors shall be determined by thermometer [or other devices such as fiber-optic probes or temperature “stickers”](#) where the use of thermocouples poses a hazard due to high voltage.

8.3.3 Ambient temperature

Ambient temperature [for an open reactor](#) is the temperature of the air surrounding the reactor [and for an enclosed reactor is the temperature of the air surrounding the enclosure](#).

8.3.4 Methods of temperature determination

8.3.4.1 Thermometer method of temperature determination

The thermometer method consists of determining the temperature by mercury or alcohol thermometers, by resistance thermometers, or by thermocouples, any of these instruments being applied to the hottest part of the apparatus accessible to mercury or alcohol thermometers.

8.3.4.2 Resistance method of temperature determination

The resistance method consists of the determination of the temperature by comparison of the resistance of a winding at the temperature to be determined, with the resistance at a known temperature.

9. Insulation levels and dielectric tests

9.1 Impulse insulation levels

The standard impulse insulation levels for series reactors are given in Table 6, column 2. These values are expressed in terms of the peak value of a $1.2 \times 50 \mu\text{s}$ full wave.

Table 6—Insulation test levels for dry-type air-core series reactors

<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>	<u>6</u>	<u>7</u>
<u>Rated system voltage (kV)^a</u>	<u>BIL and full wave test^{b,g} (kV peak)</u>	<u>Chopped-wave test^c (kV peak)</u>	<u>Time to chopping (us)</u>	<u>Switching impulse test^d (kV peak)</u>	<u>Turn-to-turn test voltage^e (kV peak)</u>	<u>Power-frequency withstand test^f (kV rms)</u>
<u>1.2</u>	<u>30</u>	<u>33</u>	<u>1.0</u>	<u>=</u>	<u>25</u>	<u>10</u>
	<u>45</u>	<u>50</u>	<u>1.5</u>	<u>=</u>	<u>38</u>	<u>10</u>
<u>2.5</u>	<u>45</u>	<u>50</u>	<u>1.5</u>	<u>=</u>	<u>38</u>	<u>15</u>
	<u>60</u>	<u>66</u>	<u>1.5</u>	<u>=</u>	<u>51</u>	<u>15</u>
<u>5.0</u>	<u>60</u>	<u>66</u>	<u>1.5</u>	<u>=</u>	<u>51</u>	<u>19</u>
	<u>75</u>	<u>83</u>	<u>1.5</u>	<u>=</u>	<u>64</u>	<u>19</u>
<u>8.7</u>	<u>75</u>	<u>83</u>	<u>1.5</u>	<u>=</u>	<u>64</u>	<u>26</u>
	<u>95</u>	<u>105</u>	<u>1.8</u>	<u>=</u>	<u>81</u>	<u>26</u>

<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>	<u>6</u>	<u>7</u>
<u>Rated system voltage (kV)^a</u>	<u>BIL and full wave test^{b,g} (kV peak)</u>	<u>Chopped-wave test^c (kV peak)</u>	<u>Time to chopping (μs)</u>	<u>Switching impulse test^d (kV peak)</u>	<u>Turn-to-turn test voltage^e (kV peak)</u>	<u>Power-frequency withstand test^f (kV rms)</u>
<u>15</u>	<u>95</u>	<u>105</u>	<u>1.8</u>	<u>—</u>	<u>81</u>	<u>34</u>
	<u>110</u>	<u>120</u>	<u>2.0</u>	<u>—</u>	<u>94</u>	<u>34</u>
<u>25</u>	<u>150</u>	<u>165</u>	<u>3.0</u>	<u>—</u>	<u>128</u>	<u>50</u>
<u>34.5</u>	<u>200</u>	<u>220</u>	<u>3.0</u>	<u>—</u>	<u>170</u>	<u>70</u>
<u>46</u>	<u>200</u>	<u>220</u>	<u>3.0</u>	<u>—</u>	<u>—</u>	<u>95</u>
	<u>250</u>	<u>275</u>	<u>3.0</u>	<u>—</u>	<u>—</u>	<u>95</u>
<u>69</u>	<u>250</u>	<u>275</u>	<u>3.0</u>	<u>—</u>	<u>—</u>	<u>140</u>
	<u>350</u>	<u>385</u>	<u>3.0</u>	<u>—</u>	<u>—</u>	<u>140</u>
<u>115</u>	<u>350</u>	<u>385</u>	<u>3.0</u>	<u>291</u>	<u>—</u>	<u>173</u>
	<u>450</u>	<u>495</u>	<u>3.0</u>	<u>375</u>	<u>—</u>	<u>173</u>
	<u>550</u>	<u>605</u>	<u>3.0</u>	<u>450</u>	<u>—</u>	<u>173</u>
<u>138</u>	<u>450</u>	<u>495</u>	<u>3.0</u>	<u>375</u>	<u>—</u>	<u>207</u>
	<u>550</u>	<u>605</u>	<u>3.0</u>	<u>460</u>	<u>—</u>	<u>207</u>
	<u>650</u>	<u>715</u>	<u>3.0</u>	<u>540</u>	<u>—</u>	<u>207</u>
<u>161</u>	<u>550</u>	<u>605</u>	<u>3.0</u>	<u>460</u>	<u>—</u>	<u>242</u>
	<u>650</u>	<u>715</u>	<u>3.0</u>	<u>540</u>	<u>—</u>	<u>242</u>
	<u>750</u>	<u>825</u>	<u>3.0</u>	<u>620</u>	<u>—</u>	<u>242</u>
	<u>825</u>	<u>900</u>	<u>3.0</u>	<u>685</u>	<u>—</u>	<u>242</u>
<u>230</u>	<u>750</u>	<u>825</u>	<u>3.0</u>	<u>620</u>	<u>—</u>	<u>345</u>
	<u>825</u>	<u>900</u>	<u>3.0</u>	<u>685</u>	<u>—</u>	<u>345</u>
	<u>900</u>	<u>990</u>	<u>3.0</u>	<u>745</u>	<u>—</u>	<u>345</u>
<u>345</u>	<u>1050</u>	<u>1155</u>	<u>3.0</u>	<u>870</u>	<u>—</u>	<u>518</u>
	<u>1175</u>	<u>1290</u>	<u>3.0</u>	<u>975</u>	<u>—</u>	<u>518</u>
<u>500</u>	<u>1425</u>	<u>1570</u>	<u>3.0</u>	<u>1180</u>	<u>—</u>	<u>750</u>
	<u>1550</u>	<u>1705</u>	<u>3.0</u>	<u>1290</u>	<u>—</u>	<u>750</u>
	<u>1675</u>	<u>1845</u>	<u>3.0</u>	<u>1390</u>	<u>—</u>	<u>750</u>
<u>735</u>	<u>1950</u>	<u>2145</u>	<u>3.0</u>	<u>1550</u>	<u>—</u>	<u>830</u>
<u>765</u>	<u>2050</u>	<u>2255</u>	<u>3.0</u>	<u>1700</u>	<u>—</u>	<u>880</u>

^a A reduced insulation level may be applied across reactor terminals if the reactor is adequately protected by a surge arrester. This could be an economical engineering solution for some series reactors installed on transmission systems such as current-limiting reactors, series capacitor discharge reactors, etc. For such cases, the insulation level across the reactor shall be one of the above standardized levels and shall be at least 1.25 times the $8 \times 20 \mu\text{s}$, 10 kA protective level of the surge arresters connected between terminals.

^b In the case of dry-type air-core series reactors employed in a three-phase stack configuration, interphase insulators may have a higher BIL rating than those at the base of the stack that provide only phase-to-ground insulation.

^c Chopped-wave test level is defined as $1.1 \times \text{BIL}$ (basic impulse insulation level) test level, including the appropriate “round-off.”

^d Switching impulse test is applicable to the support insulator only and is defined for nominal system voltages 230 kV and higher.