IEEE P57.16

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

IEEE Power and Energy

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Abstract: 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 are covered. 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, 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, IEEE Standard Requirements, Terminology, and Test Code for Dry-Type Air-Core Series-Connected Reactors.)

The work to revise ANSI C57.16-1996, 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. There were several important objectives for the revision, which 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 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 S.C. rating, but 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 only included to provide guidance and to “caution” and is not meant to “supercede” information in the referenced switchgear standards. In fact another purpose of the annex is to direct readers to the appropriate switchgear documents.

This draft standard is being developed by the Working Group for the Revision of IEEE C57.16, which has the following membership:

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

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). Annexes A, B, and 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),
b) Arc suppression coils,
c) Neutral grounding devices [see IEEE Std 32-1972 (Reaff 1990), IEEE Standard Requirements, Terminology, and Test Procedures for Neutral Grounding Devices],
d) Line resonant reactors,
e) High-Voltage direct current (HVDC) smoothing reactors (IEEE 1277-2009)
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 air-core reactors and with some restrictions filter reactors, shunt capacitor reactors and discharge current limiting 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.

ANSI C29.9-1983 (R2002), American National Standard—Wet-Process Porcelain Insulators (Apparatus, Post Type).[1]

ANSI C84.1-2006, American National Standard—Voltage Ratings for Electric Power Systems and Equipment Voltage Ratings.

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

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—Specifications for Octave-Band and Fractional Octave-Band Analog and Digital Filters.

IEC 60076-4-2002, Power transformers - Part 4: Guide to the lightning impulse and switching impulse testing of power transformers and reactors. Appendix A, Principles for waveshape control.

IEC 60076-6-2007, Power transformers - Part 6: Reactors.

IEC 60076-10-2005, Power transformers - Part 10: Determination of sound levels.

IEEE Std 1-2000 (Reaff. 2005), IEEE Recommended Practice - General Principles for Temperature Limits in the Rating of Electric Equipment and for the Evaluation of Electrical Insulation[2]

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

IEEE Std. 693-2005, IEEE Recommended Practices for Seismic Design of Substations (ANSI).

IEEE Std 824-2004, IEEE Standard for Series Capacitor Banks in Power Systems (ANSI).

IEEE Std C57.21-2008, IEEE Standard Requirements, Terminology and Test Code For Shunt Reactors Rated Over 500 kVA (ANSI).

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

NEMA CCI-2009, Electric Power Connections for Substations.[3]

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[1] ANSI publications are available from the Sales Department, American National Standards Institute, 11 West 42nd Street, 13th Floor, New York, NY 10036, USA.

[2] IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331 USA.

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

3. Definitions

All definitions, except as specifically covered in this standard, shall be in accordance with IEEE Std 100-2000 For the convenience of the user, definitions are organized by category.

3.1 Types of dry-type air-core series reactors

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

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

3.1.3 outdoor reactor: A reactor of weatherproof construction.

3.1.4 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.

3.2 Series reactor applications

3.2.1 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.

3.2.2 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 conditions, or under other operating conditions, such as capacitor switching, motor starting, synchronizing, arc stabilization, etc.

3.2.3 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 negative coupling under normal operating conditions to reduce circuit impedance and positive coupling under fault conditions to increase circuit impedance.

3.2.4 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.

3.2.5 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.

3.2.6 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.

3.2.7 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.

3.2.8 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.

3.3 Rating

3.3.1 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.

3.4.2 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.

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

3.4.4 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.

3.4.5 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

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

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

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

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

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

3.5.6 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

3.6.1 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.

3.6.2 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.

3.6.3 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, impedance, and system frequency

3.7.1 Losses

3.7.1.1 "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.

3.7.1.2 losses; Those 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—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—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

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

3.7.2.2 impedance voltage drop: The product of the rated ohms' impedance and the rated current of a series reactor.

3.7.2.3 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.

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

3.7.2.5 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.

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

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

3.7.2.8 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.[4]

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-circuit, 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:

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 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.

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[4] 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.

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.

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 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 (i.e., pollution, altitude, etc.).

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[5] for use of a correction factor with sphere gaps.

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

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[5] Information about references can be found in Clause 2.

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.

4.3.2 Operation at rated 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.

4.3.3. Operation at less than rated 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), that the current to be carried is 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.

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.

Table 2—Maximum allowable 24 h average temperature of cooling air to permit a dry-type air-core series reactor to carry rated 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 4 (see page 6).

5. Rating

5.1 Basis of rating

The rating of a series reactor shall include the following:

a) Reactance (in ohms or percent)
b) Voltage drop
c) System voltage
d) Continuous current
e) Mechanical and thermal short-circuit current
f) Number of phases
g) Frequency
h) Basic impulse insulation level (BIL)

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 (see also Clause 9).

5.5 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 will impose 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

$$X_L = \frac{(V_S)^2}{MVA} \tag{1}$$

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

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

$$I_{SC} = \frac{MVA}{\sqrt{3} \cdot V_S}, I_{SC} = \frac{V_S}{\sqrt{3}} \cdot \frac{1}{X_L} \tag{4}$$

> 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 (about the middle of Table 7, Clause 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 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

$$X_L = \frac{(3.8 \cdot 1.05)^2}{100} = 2.1\Omega \tag{5}$$

The total series reactance required to limit fault level to 50 MVA and accounting for a nominal operating overvoltage of 105% is

$$X_L = \frac{(3.8 \cdot 1.05)^2}{50} = 4.20\,\Omega \tag{6}$$

Therefore, the required value of the series reactor reactance is

$$X_R = 4.20 - 2.1 = 2.10\ \Omega \tag{7}$$

The symmetrical rms fault-current rating of the reactor is

$$I_{SCA} = \frac{(3.8 \cdot 1.05)}{\sqrt{3}} \cdot \frac{1}{4.2} = 2.0\,kA \tag{8}$$

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) must 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 asymmetrical amperes. The maximum crest of an asymmetrical current shall be determined by the purchaser through system knowledge and the use of Equation (9), Clause 10.2.2. If not specified by the purchaser, the maximum crest asymmetrical current shall be considered as 2.55 times the rms symmetrical current ($I_{pk} = 2.55 \bullet I_{rms}$).

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, 2, 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. For fiberglass enclosures, large metallic auxiliary parts (e.g., ventilation screens) shall be grounded so as 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	When performed	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.	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		
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			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 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 becomes part of the commercial contract. A tolerance on losses, to account, for instance, for measurement tolerances etc., may be part of the contractual agreement. 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.

The only warning that should be stressed is 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 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 3-phase stacks it is permissible to assemble only one 3-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 3-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 depend 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 are 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 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 1-2000.

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. 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 C57.21-2008) 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.

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. 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 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. Specifically, series reactors shall be so designed that the hottest-spot conductor temperature rise above the ambient temperature when operated at rated current will 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 (°C)**	**Average winding temperature rise by resistance** (°C)	**Hottest-spot winding temperature rise (°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.		

NOTES

1—Temperature rise is rise above ambient in degrees Celsius.

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

3—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 ensures an element of conservatism in the thermal performance of an insulation system and thus constitutes part of the experience factor in assigning temperature rise limits.

4—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 vs. outdoor service, high continuous duty (limited "load cycling"), and loading profile (specified overloads).

5—The average winding temperature rise limits are based on the attempt to achieve an approximate 40% differential 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 hot spot temperature rise that determines the life of a reactor, based on agreement between the manufacturer and purchaser, the average temperature rise can be safely exceded for some reactor designs provided the hot spot rise limit is respected and verified.

6—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

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** °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

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], [B6] and [B16] can be consulted. The table above provides basic guidelines.

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 to ensure that the dimensions and the direction of approach of the user's conductors are such as to 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 will radiate 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 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.

NOTES

1—When the available test power does not permit making the test at rated current, then the manufacturer shall demonstrate to the user that reduced current testing produces sufficiently accurate results when extrapolated to rated current level. The manufacturer shall notify the user of reduced current level testing during the proposal stage.

2—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 fibre optic probes or temperature “stickers” where the use of thermocouples poses a hazard due to high voltage.

8.3.3 Ambient temperature

Ambient temperature is the temperature of the air surrounding the reactor.

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 crest value of a 1.2 x 50 µs full wave.

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

Nominal System voltage (kV)[1,2]	BIL and full wave test [3,8] (kV peak)	Chopped – wave test [4] (kV peak)	Time to chopping (µs)	Switching impulse test[5] (kV peak)	Turn-to-turn test voltage[6] (kV peak)	Applied voltage test[7] (kV r.m.s.)
1.2	30	33	1.0	-	25	10
	45	50	1.5	-	38	10
2.5	45	50	1.5	-	38	15
	60	66	1.5	-	51	15
5.0	60	66	1.5	-	51	19
	75	83	1.5	-	64	19
8.7	75	83	1.5	-	64	26
	95	105	1.8	-	81	26
15	95	105	1.8	-	81	34
	110	120	2.0	-	94	34
25	150	165	3.0	-	128	50
34.5	200	220	3.0	-	170	70

Table 6-Insulation test levels for dry-type air-core series reactors *(continued)*

Nominal System voltage (kV)[1,2]	BIL and full wave test [3,8] (kV peak)	Chopped – wave test[4] (kV peak)	Time to chopping (µs)	Switching impulse test[5] (kV peak)	Turn-to-turn test voltage[6] (kV peak)	Applied voltage test[7] (kV r.m.s.)
46	200	220	3.0	-	-	95
	250	275	3.0	-	-	95
69	250	275	3.0	-	-	140
	350	385	3.0	-	-	140
115	350	385	3.0	291	-	173
	450	495	3.0	375	-	173
	550	605	3.0	450	-	173
138	450	495	3.0	375	-	207
	550	605	3.0	460	-	207
	650	715	3.0	540	-	207
161	550	605	3.0	460	-	242
	650	715	3.0	540	-	242
	750	825	3.0	620	-	242
	825	900	3.0	685	-	242
230	750	825	3.0	620	-	345
	825	900	3.0	685	-	345
	900	990	3.0	745	-	345
345	1050	1155	3.0	870	-	518
	1175	1290	3.0	975	-	518
500	1425	1570	3.0	1180	-	750
	1550	1705	3.0	1290	-	750
	1675	1845	3.0	1390	-	750
735	1950	2145	3.0	1550	-	830
765	2050	2255	3.0	1700	-	880

[1] Nominal system voltage applies to the phase-to-ground insulation levels.

[2] 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 x 20 µs, 10 kA protective level of the surge arresters connected between terminals.

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

[4] Chopped-wave test level is defined as 1.1 x BIL (basic impulse insulation level) test level; including

the appropriate "round off".

[5] Switching impulse test is applicable to the support insulator only and are defined for nominal system voltages 230 kV and higher.

[6] Turn-to-turn test levels are defined for BIL equal to or less than 200 kV. Turn-to-turn test levels are defined to be 90% of the rated BIL across reactor terminals. For BIL voltages greater than 200 kV, the turn-to-turn test is not applicable and a full-wave impulse test is to be performed as a routine test. Although the WG considered extending the turn-to-turn test up to BIL equal to or less than 550kV, it was decided not to include test values in Table 5 as fully commercialized test equipment was not readily available or fully proven. However the option remains to employ a turn-to-turn test at higher BILs based on a crest voltage of 85% of BIL. Performance of the turn-to-turn test in lieu of the impulse test would be based on the availability of test equipment and agreement between the manufacturer and the purchaser.

[7] Applied voltage test is applicable to the support insulator only.

[8] For reactors installed indoors the "end user" may specify a reduced BIL.

9.2 Dielectric test levels

Standard impulse and low-frequency dielectric test levels for series reactors shall be as given in Table 6.

9.3 Dielectric

9.3.1 Dielectric tests

Dielectric tests are tests that consist of the application of a voltage higher than the rated voltage for a specified time for the purpose of determining the adequacy against breakdown of insulating materials and spacing under normal conditions.

9.3.2 Turn-to-Turn overvoltage test

The turn-to-turn test for dry-type air-core series reactors shall be made by applying between the terminals of each winding a series of high-frequency, exponentially decaying sinusoidal voltages. The test sequence shall consist of a reduced sinusoidal voltage discharge followed by 7200 sinusoidal voltage discharges with a first peak voltage at least equal to the values specified in Table 6, column 6. The duration of the test shall be such that the required number of voltage peaks of specified magnitude are achieved.

> Note—Test duration required to meet the 7200 sinusoidal voltage discharges is a function of the charging circuit employed.

9.3.3 Impulse tests

For dry-type air-core series reactors, a lightning impulse test shall be made on each terminal of the reactor by applying a reduced wave and three full waves, all of positive polarity with crest voltage as specified in Table 6, column 2.

> Note—All impulse tests in IEEE reactor standards are positive polarity. Positive polarity impulses provide a more onerous test on external insulation than negative polarity impulses.

A chopped wave impulse test is an "other" test and shall be made on each terminal of the reactor, when specified, by applying one reduced full wave, one full wave, one reduced chopped wave, two chopped waves, followed by two full waves (preferably within 10 min after the last chopped wave), with crest voltage as specified in columns 2 and 3 of Table 6 and time to chop as specified in column 4 of Table 6.

> Note—Based on agreement between purchaser and manufacturer, consideration can be given to performing an optional procedure for the impulse design test for series reactors rated 230 kV and higher. This optional procedure is proposed to be consistent with other substation equipment employing mixed insulation systems (bushings, instrument transformers, circuit breakers, etc.). This optional procedure is only applicable to sub-transmission and transmission class reactors. The objective is for the number of impulses applied to each terminal to be statistically significant. Procedure B of IEEE Std. 4-1995 provides guidance. If such an optional procedure is required, it shall be clearly indicated in the user's enquiry. It is also recommended that consideration be given to performing this "optional" impulse design test on a "mock-up" due to the statistical nature of the test and the fact that two flashovers are allowed. This "mock-up" should consist of the complete end electrode geometry and a single layer winding of the rated inductance. The cost of the "mock-up" should be included in the cost of this "optional" impulse design test. Equivalent type test reports may be submitted in lieu of performing the test.
>
> In this case, the lightning impulse design test shall 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 shall 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
>
> Due to the statistical nature of the test, 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 non self-restoring insulation.

A switching impulse test under wet conditions test shall be made, when specified, on the complete support assembly, including the reactor and insulators, for system voltages 230 kV and higher. The test voltage is of positive polarity. The test shall include one reduced and 15 full waves, with crest voltage as specified in Table 5, column 5. Two disruptive discharges (flashovers) are allowed. The purpose of this test is to assess the effect of the geometry of the reactor and ancillary elements of the support structure on the switching impulse withstand of the support insulators. The simulated rain conditions shall be in accordance with IEEE Std 4-1995. The simulated rain conditions shall be met on only one of the supporting insulator structures if more than one insulator structure is used.

9.3.4 Applied voltage test

For dry-type air-core series reactors an applied voltage test shall be made, when specified, on the reactor's supporting structure, including insulators. For outdoor applications and system voltages equal to or greater than 230 kV, the test shall be made under simulated wet conditions. The simulated rain conditions shall be in accordance with IEEE Std. 4-1995. The simulated rain conditions shall be met on only one of the supporting insulator structures if more than one insulator is used. Test values are those indicated in Table 6, column 7.

9.3.5 Radio influence voltage (RIV) test

The RIV test is only required for series reactors operating at system voltages 230 kV and higher and is carried out at power frequency according to NEMA 107-1987 (R1993). The radio influence voltage of a series reactor shall not exceed the maximum RIV value stated in Table 7, when the series reactor is applied at the stated maximum system voltage. The RIV test shall be performed on the reactor, its support structure and connectors, if available. The main sources of radio noise are the auxiliary metallic components of the reactor, such as the end electrodes, terminals, insulator mounting brackets, etc.

Table 7—Radio influence voltage

System voltage (kV)[a]		Radio influence test voltage (kV)[b]	Maximum radio influence voltage (μV)[c]
Maximum	Nominal		
242	230	140	250
362	345	209	250
550	500	317	500
800	765	462	750

[a] The maximum and nominal system voltages are from ANSI C84.1-2006 American National Standard for Electric Power Systems and Equipment—Voltage Ratings.

[b] The radio influence test voltage is the line-to-ground value of the maximum system voltage.

[C] The maximum permissible background RIV level will be 1/2 of the maximum radio influence voltage level (μV) tabulated for each system voltage. Correction for background voltage level shall be by the rms method. These maximum radio influence voltages, as conducted radio noise, will add a negligible amount to the radio noise normally radiated from the line, even at a short distance from the series reactor and its support structure.

10. Short-Circuit capability

10.1 Short-Circuit description

10.1.1 Duration

The duration of the short circuit is limited to 3 s or as specified by the purchaser.

10.1.2 Requirements

When used on circuits having reclosing features, series reactors (current-limiting application) shall be capable of withstanding successive short circuits without cooling to normal operating temperatures between successive occurrences of the short circuit, provided the accumulated duration of short circuit does not exceed 3 s or a duration specified by the purchaser.

10.1.3 Operating conditions

Some of the operating conditions that may result in short-circuit currents in excess of those provided for normal operating conditions are listed below:

a) The short-circuit current will be increased when the series reactor is operated above 105% rated system voltage and a short circuit occurs during a period of such operation.
b) The fault currents may be increased during abnormal conditions, such as out-of-phase voltage conditions on interconnected systems.

10.2 Maximum mechanical stress of series reactors for short-circuit conditions

10.2.1 Initial short-circuit current

For determination of maximum mechanical stresses, the initial short-circuit current shall be assumed to be offset. In a system with zero damping, the maximum crest value of the short-circuit current is two times the crest value of the rms symmetrical short-circuit current. In reality, however, the value is lower due to system damping effects.

10.2.2 First cycle asymmetrical peak

The first cycle asymmetrical peak short-circuit current that the reactor is required to withstand shall be specified by the purchaser or, based on knowledge of system damping, can be determined as below. If not specified by the purchaser, the maximum asymmetrical crest value of short-circuit current should be considered to be 2.55 times the rms symmetrical current.

$$I \text{ (peak asymmetrical)} = K I_{sc} \tag{9}$$

where

I_{sc} is the short-circuit current, rms symmetrical, and

K *is* 2.55, or the appropriate multiplier obtained from Table 8.

NOTES

1-The 2.55 value for the asymmetry factor *K* is based on a dc offset of 1.8 vs. the theoretical maximum value of 2.0. The assumption that a minimum value of system damping is always present is consistent with the practice in IEC standards; including IEC 60076-6-2007 i.e., $K = 1.8$ • ..

2-The *X/R* ratio in Table 7 is a measure of damping in the system or circuit in question. *R* is the effective resistance of the system including the reactor, and *X* is the net reactance in the system including that supplied by the reactor.

Table 8-Value of K for use in Equation (9)

X/R	*K*	*X/R*	*K*	*X/R*	*K*
1000	2.824	100	2.785	10	2.452
500	2.820	50	2.743	5	2.184
333	2.815	33	2.702	3,3	1.990
250	2.811	25	2.662	2,5	1.849
200	2.806	20	2.624	2	1.746
167	2.802	17	2.588	1	1.509
143	2.798	14	2.552		
125	2.793	12,5	2.518		
111	2.789	11	2.484		
-	-				

10.2.3 Asymmetry factor *K*

The multiplier *K* is calculated from

$$K = \left[+ \varepsilon^{-\Phi \quad \pi \quad 2)R/X} \right) \sin\Phi \Big]\sqrt{2} \tag{10}$$

where

R/X is the ratio of ohms resistance to ohms reactance in the system when the short circuit occurs,

ε is 2.7183, the base of the natural logarithms, and

ϕ is the $\tan^{-1}$ (*X/R*), in radians.

NOTE-The expression for K is an approximation. The values of K given in Table 8 are calculated from this approximation and are accurate to within 0.7% of the values calculated by exact methods.

NOTE – For reactor applications involving shunt or series capacitor banks k factor cannot be used. The purchaser shall specify the peak short circuit current considering the actual circuit configuration.

10.3 Thermal limit of series reactors for short-circuit conditions

10.3.1 Limiting temperature

The temperature, as calculated by methods given in 11.7.1, of the conductor material in the windings of reactors under the short-circuit conditions specified in 10.1 shall not exceed the limiting values given in Table 9.

Table 9—Limiting temperature for rated short-term current

Insulation temperature index (°C)	**Actual limiting temperature** (°C)[1]
105	205
130	285
155	315
180	350
220	400

[1] The above limiting temperatures are upper bounds based on the known capabilities of available materials. The actual limit used on design shall be modified based on the winding insulation and encapsulation materials utilized.

10.4 Mechanical short-circuit test

10.4.1 Mechanical strength capability

The test for the mechanical strength capability of the series (current-limiting) reactor shall be made at a specified test current for a duration of not less than 10 cycles at rated frequency with the first maximum crest value of the completely offset short circuit not less than the maximum crest value as given in 10.2.2 or as specified by the purchaser.

11. Test code

11.1 General

11.1.1 Symbols

In this test code an effort is made to use a uniform set of symbols, without, however, sacrificing simplicity or clarity. Following are the main symbols:

E	voltage
I	current
P	active power (in-phase component)
Q	reactive power (quadrature component)
kVA or VA	apparent power
Z	impedance
R	resistance
X	reactance
L	inductance, self
C	capacitance
θ	temperature, as indicated, in degrees Celsius
$C\theta$	thermal capacitance, heat capacity
T	time
ϕ	impedance angle, in degrees
F, m, a, k	factor, as indicated

11.1.2 Subscripts and symbols

Subscripts and other symbols will be used as locally identified.

11.1.3 Schedule of tests

The usual program of testing a reactor includes some or all of the following tests:

Tests	Subclause
Resistance measurements	11.2
Dielectric tests	11.3
Losses and impedance	11.4
Temperature rise	11.5
Short-Circuit test	11.6
Short-time current	11.7

11.2 Resistance measurements

11.2.1 Necessity for resistance measurements

Resistance measurements are of fundamental importance for three purposes:

a) For the calculation of the conductor 1^{2}R loss.

b) For the calculation of winding temperatures at the end of a temperature rise test.

c) For a quality check among units of the same rating.

11.2.2 Conversion of 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 and loss measurements were made. The conversions are accomplished by the following formula:

$$R_s = R_m \left(\frac{\theta_s + \theta_k}{\theta_m + \theta_k} \right) \qquad (11)$$

where

R_s is the resistance at desired temperature θ_s,

R_m is the measured resistance at temperature θ_m,

θ_s is the desired reference temperature, in degrees Celsius,

θ_m is the temperature at which resistance was measured, in degrees Celsius, and

T_k is 234.5 (copper), 225 (aluminum).

NOTE—The manufacturer shall use the appropriate value of T_k for the specified conductor material used and shall advise the purchaser accordingly.

11.2.3 Determination of cold temperature

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

11.2.3.1 General

Cold resistance measurements shall not be taken in less than 4 h after the reactor has been moved from one location to another where the ambient temperatures differ by more than 5 °C, but less than 10 °C. Measurements shall not be taken in less than 8 h if the temperature difference is more than 10 °C.

NOTE—The above guidelines apply to dry-type air-core series reactors with typical thermal time constants between 30 and 60 min. In the case of very large reactors with a thermal time constant over 60 min, the waiting times should be increased to 5 and 10 times the actual thermal time constant, respectively.

11.2.3.2 Reactor windings

The temperature of the windings shall be recorded as the average of several thermocouples or thermometers or other temperature measurement devices located along the winding with extreme care used to ensure that their functional end or bulbs are as nearly as possible in actual contact with the windings. It should not be assumed that the windings are at the same temperature as the surrounding air.

11.2.3.3 Drop-of-Potential method (Volt-Ampere)

11.2.3.3.1 Equipment

DC resistance for reference, for losses calculation and for the temperature rise test can be measured using the drop of potential (voltmeter-ammeter) methods as described in Clauses 12.2.3.3.2 & 12.2.3.3.9 or by using electronic based micro-ohm-meters which are based on the four wire volt-ampere methodology. The use of micro-ohm-meters is especially recommended for the temperature rise test.

Since the use of a micro-ohmeter provides direct readout of dc resistance, the methodology described below only applies to drop-of-potential (volt-ampere) methodology.

The drop-of-potential method is generally more accurate than the bridge method for measurements made in the field as the possibility to use higher dc current can overcome interference issues.

11.2.3.3.2 Simultaneous readings

Measurements are made with direct current, and simultaneous readings of current and voltage are taken using the connections of Figure 1. The required resistance is calculated from the readings in accordance with Ohm's law.

11.2.3.3.3 Errors of observation

In order to minimize errors of observation, the measuring instruments insofar as possible shall have such ranges as will give reasonably large deflections or, if digitally based, they shall provide readouts of several significant digits accurately.

11.2.3.3.4 Voltmeter leads

The voltmeter leads shall be connected as closely as possible to the terminals of the winding to be measured. This is to avoid including in the reading the resistances of current-carrying leads and their contact and of extra lengths of leads.

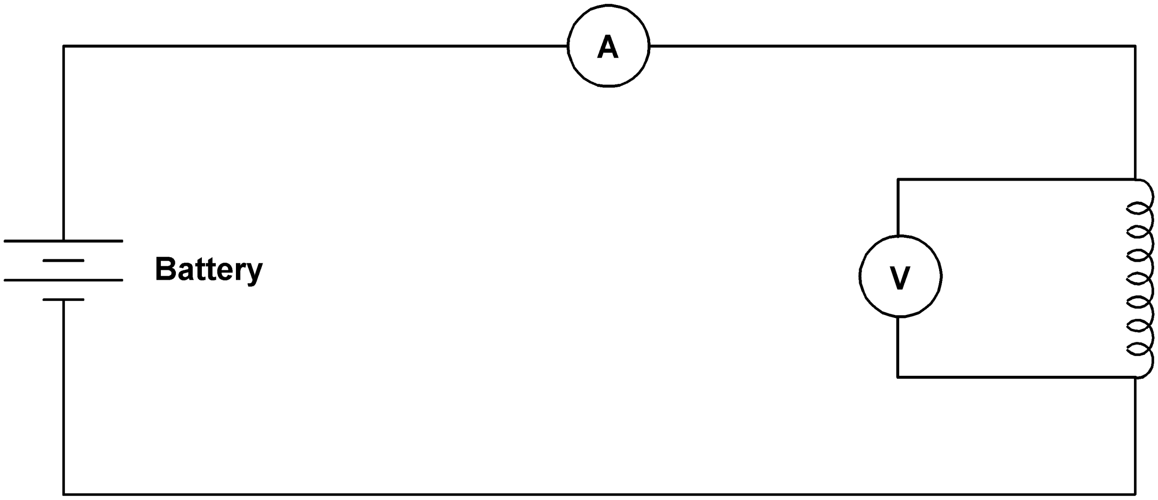


Figure 1 – Connections for the drop-of-potential method of resistance measurement

11.2.3.3.5 Voltmeter protection To protect the voltmeter from injury by off-scale deflections, the voltmeter should be disconnected from the circuit before switching the current on or off.

11.2.3.3.6 Accuracy

Voltmeters and ohmmeters of suitable range and accuracy shall be used.

11.2.3.3.7 Steady-State values

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

11.2.3.3.8 Number of readings

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

11.2.3.3.9 Percent of rated continuous current

The current used shall not exceed 15% of the rated continuous 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.

11.2.3.4 Bridge methods

Bridge methods are a preferred because of their accuracy and convenience.

11.2.3.4.1 Bridge methods

Bridge methods are also recommended for measurements that are to be used in connection with temperature-rise determination.

11.2.3.4.2 "Thermoelectric effects"

In order to avoid "thermoelectric effects" that are more pronounced when measuring hot dc resistance, the leads for connection to the bridge, including the mechanism utilized to connect to the reactor terminals, should be of the same material as the windings and terminals of the reactor on which measurements are being made—e.g., copper for copper-wound reactors, and aluminum for aluminum-wound reactors.

11.3 Dielectric tests

11.3.1 Methodology

Unless otherwise specified, dielectric tests shall be made in accordance with IEEE Std 4-1995. Dielectric tests apply also to reactors in enclosures with built-in leads when they are so furnished.

11.3.2 Factory dielectric tests

11.3.2.1 Purpose

The purpose of dielectric tests in the factory is to check the insulation and workmanship and to demonstrate that the reactor has been designed to withstand the insulation tests required by the purchase specification.

11.3.3 Applied-Voltage test

11.3.3.1 General

In the case of dry-type air-core series reactors, the major insulation to ground is supplied by the support insulators. Therefore an applied voltage test is a test on the support insulators.

11.3.3.2 Method

For reactors having system voltages equal to or greater than 230 kV, the test shall be performed under simulated rain conditions. Test values are those indicated in Table 6, column 7. The simulated rain conditions shall be in accordance with IEEE Std 4-1995. The actual reactor or an equivalent "mock-up" shall be mounted on the insulating support structure. The simulated rain conditions shall be considered to be met using only the reactor or mock-up section facing the simulated rain producing equipment and on only one of the supporting insulator structures, if more than one supporting insulator structure is used. The rationale for this test set up is that the reactor winding surfaces can act as a rain collector and increase the quantity of rain on the insulating structure.

11.3.4 RIV test

The RIV test shall be performed at power frequency with the series reactor suitably supported in order to determine the RIV produced by the series reactor itself. If the field-installed support structure is available, then the test shall be carried out in this configuration. Actual connectors should be used if available. If not available, equivalent or similar connectors should be used with the in-service feeding conductors simulated with aluminum pipes or cables of equivalent diameter. The aluminum pipe or cable length shall be greater than one meter for each reactor terminal. At the end of the aluminum pipe or cable, suitable corona shielding may be used by the laboratory. The equipment and general method used in determining the RIV shall be in accordance with the criteria in Annex A of NEMA CC1-2009. The RIV shall not exceed the value in accordance with 9.3.5 and Table 7.

11.3.5 Turn-to-Turn overvoltage test for dry-type air core series reactors

11.3.5.1 Background

The turn-to-turn test is equivalent to the lightning impulse test as a "quality" check. As such test levels should not be more severe than the impulse test. The turn-to-turn test is convenient and practical and failure detection, especially with digital data acquisition systems, is definitive.

NOTE—Therefore, at the time of revision of this standard the WG considered whether the turn-to-turn test should be extended from 34.5 kV system voltage class to 115 kV system voltage class as an alternative to the impulse test; equivalent to 550 kV BIL. However, since fully commercialized test equipment was not readily available and proven, it was decided not to include specific test levels at this time and thus will be left to another revision process. The option does remain based on availability of test equipment and agreement between manufacturer and end user, to perform a turn-to-turn test in lieu of an impulse test for higher BIL ratings.

11.3.5.2 Test Methodology

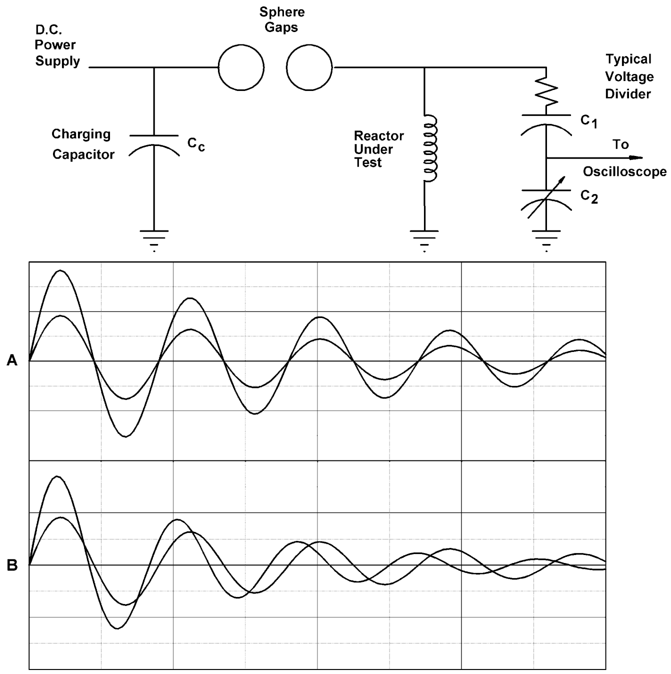
The turn-to-turn test is performed by repeatedly charging a capacitor and discharging it, through sphere gaps, into the reactor windings. The type of overvoltage that the reactor is subjected to is more representative of a switching overvoltage, with an exponentially decaying sinusoidal waveshape and a front time similar to a lightning impulse. The duration of the test shall be such that the required number of voltage peaks of specified magnitude are achieved and the initial crest value shall be the peak value as specified in Table 6. The ringing frequency is a function of the coil inductance and charging capacitor, and is typically on the order of 1 kHz to 100 kHz. The test shall consist of not less than 7200 overvoltages of the required magnitude.

Primary verification of winding insulation integrity should be based on "oscillographic" methods. A surge oscilloscope and camera or digital data acquisition system are used to record the last discharge superimposed on a reduced voltage discharge. A change in period or rate of envelope decay, between the reduced and full waves, are indications of a change in coil impedance and thus an interturn failure. The crest test voltage level is given in column 6 of Table 6.

Secondary verification of insulation integrity is by observation. A failure can be detected by noise, smoke, or spark discharge in the reactor windings.

NOTE—The test voltage for the turn-to-turn test is applied to one terminal only since any non-linearity effects due to the rate of rise to the first crest voltage of each train of decaying sinusoidal overvoltages are of little impact and secondary to the overall test objective of ensuring that the winding is subjected to a sustained decaying sinusoidal overvoltage.Figure 2 shows the schematic of the test circuit and representative oscillograms of applied test voltage. The use of oscillograms for failure detection is based on change in ringing frequency and a change in rate of envelope decay (damping).

NOTE—Test duration required to meet the 7200 sinusoidal voltage discharges is a function of the charging circuit employed.



A: Oscillogram showing a reactor that passed the turn-to-turn test.
B: Oscillogram showing a reactor of the same rating as in Oscillogram A, but having a turn-to-turn fault. Note the shift in frequency and the increased damping.

Figure 2—Turn-to-Turn test circuit and sample oscillograms

11.3.6 Standard impulse tests

A lightning impulse test is required as a routine test for dry-type reactors with nominal system voltages greater than 115 kV. The test shall consist of and be applied in the following order: one reduced full wave and three full waves. Both terminals of the reactor shall be tested. Dry-Type series reactors 34.5 kV and below shall be tested only when specified. Dry-Type reactors rated 34.5 kV and lower shall be tested with the turn-to-turn overvoltage test.

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, two chopped waves, and two full waves (preferably within 10 min after the last chopped wave).

Please note that other reduced full waves may be applied at any time during the test sequence as deemed necessary.

Impulse tests apply also to reactors fitted in enclosures with built-in leads when they are so furnished.

Refer to IEEE Std C57.98-1994 for guidance on impulse testing techniques, interpretation of oscillograms, and failure detection criteria.

> NOTE—As presented in the note in 9.3.3, and based on agreement between purchaser and manufacturer, if the optional procedure for the impulse design test is to be performed, it should consist of one reduced wave of positive polarity and 15 full waves of positive polarity applied to each terminal. Note that this optional procedure is only applicable to sub-transmission and

transmission class reactors. 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

Due to the statistical nature of the test, 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 non self-restoring insulation.

It is recommended that consideration be given to performing the “optional” impulse test on a “mock-up” due to the statistical nature and risk of flashover; two are allowed. The cost of “mock-up” should be included in the cost of this “optional” type-test. The mock-up should include the end electrodes and one winding of the rated inductance. Equivalent type test reports may be submitted in lieu of performing the test.

11.3.6.1 Full-Wave test

The full wave rises to crest in about 1.2 µs and decays to one-half of crest value in 50 µs from the virtual time zero. The crest value shall be in accordance with the assigned BIL, Table 5, subject to a tolerance of ±3%. The tolerance on time to crest should normally be ±30%. For convenience in measurement, the time to crest may be considered as 1.67 times the time interval measured on the front of the wave from 30% to 90% of the crest value. The tolerance on time to one-half of crest shall normally be ±20%. However, as a practical matter, for cases where the front time exceeds the maximum value of 1.56 µs, the impulse generator series resistance should be reduced, which should cause an overshoot on the voltage peak. The resistance shall be reduced up to the point where the overshoot does not exceed 10%. The resultant front time, obtained when the limit of 10% on the overshoot is reached shall be used for the test, even if this front value exceeds the maximum specified value of 1.56 µs.

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, the manufacturer shall advise the purchaser at proposal stage of the wave shape limitation. Based on agreement, waves of shorter duration are acceptable.

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.

If 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. If the period of these oscillations is 2 µs or more, the actual crest value shall be used.

11.3.6.2 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 given in Table 5.

11.3.6.3 Chopped-Wave test

When specified, this wave shall be the same as a full wave except that the crest value shall be at the required higher level given in Table 5 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 and the impedance shall be limited to that of the necessary leads to the gap; however, it shall be permissible 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. The value of resistance added shall not increase the time to chop of the chopped wave.

11.3.6.4 Wave polarity

For dry-type series reactors, the test wave shall be positive polarity unless otherwise specified.

11.3.6.5 Wave-Shape control

The maximum half value time t_2 of an impulse wave tail can be derived from the resonance frequency of the impulse generator capacitance *(C_8)* with the test object reactance *L_t).*

$$t_2 = \frac{\pi}{3}\sqrt{L_t C_g} \qquad (12)$$

This is a theoretical value applying to an undamped oscillation with an opposite polarity peak of 100%. Various amounts of circuit damping will reduce this value accordingly. For instance, with a limitation of 50% for the opposite polarity peak, t_2 is

$$t_2 \approx \sqrt{0.5 L_t C_g} \qquad (13)$$

Equations (12) and (13) are based on the standard impulse test circuit. Values of $t_2 < 50$ µs are typical for low-inductance reactors. Values of t_2 close to or exceeding those calculated using equations (12) and (13) can be achieved with the use of an inductor in parallel with the series (front) resistor of the impulse circuit with compromises generally required between wave duration, opposite polarity peak, wave front time, and peak overshoot.

More information on the testing of low impedance windings can be found in 1EC 60076-4., Principles of Wave Shape Control, pp. 39-47.

Note—Past practice has been to test a low-impedance winding by inserting a resistor of not more than 500 Ω in the grounded end of the winding. Although this improved the impulse wave shape, the largest portion of the test voltage was across the resistor and not across the test coil windings. Therefore, a shorter impulse wave tail is preferable to the insertion of a series resistor between the test object and ground.

11.3.6.6 Impulse oscillograms

All impulses applied to a reactor shall be recorded by a cathode-ray oscillograph or by suitable digital transient recorder. These oscillograms shall include voltage and ground-current oscillograms for *all* full-wave and reduced full-wave impulses. Sweep times should be on the order of 2 µs to 5 µs for chopped-wave tests, 50 µs to 100 µs for full-wave tests, and 100 µs to 600 µs for ground-current measurements.

All voltage and current oscillograms shall be included in the test report, including all relevant calibration shots.

11.3.7 Connections for impulse tests

The tests shall be applied to each terminal one at a time.

11.3.7.1 Terminals not being tested

One terminal of the winding under test shall be grounded through a low-resistance shunt so that ground current measurements can be made. The resistance of the current shunt should typically be less than 0.1% of the reactance of the test object (reactor) at 5 kHz. The 5 kHz reference frequency is based on the half period of a standard lightning impulse being on the order of 100 µs.

11.3.8 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.

11.3.8.1 Ground current oscillograms

In this method of failure detection, the impulse current in the grounded end of the winding tested is measured by means of a cathode-ray oscillograph or by suitable digital transient recorder connected across a suitable shunt inserted between the grounded end of the winding and ground. Any differences in the wave shape between the reduced full wave and final full wave detected by comparison of the two current oscillograms may be indications of failure or deviations due to noninjurious causes. A complete investigation is required and should include an evaluation by means of a new reduced-wave and full-wave test. Examples of probable causes of different wave shapes are operation of protective devices or conditions in the test circuit external to the series reactor.

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

It is difficult to shield the measuring circuit completely from the influence of the high voltage of the surge generator, and some stray potentials are frequently picked up that may produce an erratic record for the first 1 µs or 2 µs. Such influences, if they occur at the start of the current wave (and, to a lesser extent, at the start of the voltage wave), should be disregarded.

Where the impedance of the series reactor tested is high with respect to its series capacitance, current measurements may be difficult to make because of the small impulse current. In order to reduce the initial large capacitance current and maintain a reasonable amplitude for the remainder of the wave, a capacitor may be included in the current-measuring circuit. The capacitor should not be larger than required to achieve this result.

11.3.8.2 Voltage oscillograms

Any unexplained differences between the reduced full wave and final full wave detected by comparison of the two voltage oscillograms, or any such differences observed by comparing the chopped waves to each other and to the full wave up to the time of flashover, are indications of failure. Deviations may be caused by conditions in the test circuit external to the series reactor and shall be fully investigated and confirmed by a new reduced-wave and full-wave test.

Other techniques that can be employed to investigate a suspected problem during the impulse test are the application of additional reduced waves and the subsequent comparison of these oscillograms with the original, the application of a series of full-wave impulses and an examination of the oscillograms for evidence of progressive change and, if a digitally based test system is being employed, the transfer function can be utilized.

11.3.8.3 Other methods of failure detection

Other methods of failure detection include the following:

a) *Failure of gap to flashover*. In making the chopped-wave test, failure of the chopping gap, or any external part to flashover, although the voltage oscillogram shows a chopped wave, is a definite indication of a failure either within the series reactor or in the test circuit, or the gap is too wide.

b) *Noise*. Unusual noise within the series reactor at the instant of applying the impulse is an indication of trouble. The cause of such noise shall be investigated.

11.3.9 Switching impulse test procedures

The switching impulse test, when specified, shall consist of applying a switching impulse wave across the complete reactor support structure, including insulators, with a crest value equal to the specified test level. Since this is a test on the support structure, the reactor terminals shall be connected together during the performance of the test. In this case, due to the very large geometries involved, the switching impulse test is performed while wetting a section of the reactor and at least one insulator column. Accurate results will be obtained since all insulator columns are identical in terms of geometry. The test shall be carried out in accordance with IEEE Std 4-1995.

11.3.9.1 Number of tests

The switching impulse test consists of applying to the top of the support structure with the bottom end grounded, one reduced voltage wave and 15 full voltage waves. The reduced-voltage wave shall have a crest value of 50% to 70% of the full-voltage wave value given in Table 5. The full-voltage wave shall have a crest value in accordance with Table 5. The requirements of the test are satisfied if not more than two disruptive discharges occur.

11.3.9.2 Switching impulse waves

11.3.9.2.1 Polarity

For dry-type high-voltage series reactors, rated 230 kV and over, the test wave is normally of positive polarity.

11.3.9.2.2 Wave shape

The switching impulse voltage wave shall have a crest value in accordance with the assigned insulation level, subject to a tolerance of ±3%. The nominal time to crest shall be 250 μs ±20% and the time to half value of 2500 μs ± 60%.

11.3.9.2.3 Time to crest

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

11.3.9.2.4 Time to half-voltage values

See IEEE Std 4-1995.

11.3.9.2.5 Failure detection

A voltage oscillogram shall be taken of each impulse wave. The test is considered successful if there is no collapse of voltage indicated on the oscillograms.

11.3.9.2.6 Suggested methods of generating switching impulse waves

An applied voltage wave of proper magnitude and duration may be obtained by discharging an impulse generator or other capacitor bank across the support structure (including insulators) under test. External circuit parameters may be used for controlling the wave shape.

11.4 Losses and impedance

11.4.1 General 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.

11.4.1.1 Separation by calculation

It is not practical to measure these components separately, but after the total impedance loss and impedance voltage are measured, the components may be separated by calculation.

11.4.1.2 Resistance and reactance component determination

Resistance and reactance components of the impedance voltage are determined by the use of the following equations:

$$E_r = \frac{P_z}{I} \tag{14}$$

$$E_x = \sqrt{E_z^2 - E_r^2} \tag{15}$$

where

E_r is the resistance voltage, in phase component,

E_x is the reactance voltage, quadrature component,

E_z is the impedance voltage of winding carrying current,

P_z is the watts measured in impedance test of winding carrying current, and

I is the current in amperes in winding on which voltage is impressed.

11.4.1.3 Impedance of three-phase stacked reactors

For three-phase stacked reactors where the coupling factor between phases exceeds 5%, the current in each phase shall be measured while applying a system of symmetrical three-phase voltages to the “star-connected” phase windings. The impedance shall be taken as

$$\frac{phase - - phaseappliedvoltage}{\sqrt{3}\, xmeasuredphasecurrent}$$

11.4.2 Temperature correction for losses

The I^2R component of the impedance loss increases with the temperature, the stray-loss component diminishes with the temperature, and therefore, 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,

$$P_r = P_r' \frac{T_k + \theta}{T_k + \theta'} \tag{16}$$

$$P_S = P_S' \frac{T_k + \theta'}{T_k + \theta}$$

where

T_k is 234.5 for copper, and
T_k is 225 for aluminum.

P_r and P_s are I^2R and stray losses, respectively, at the specified temperature θ. P'_r and P'_S are measured I^2R and stray losses at temperature θ' . θ and θ' are in degrees Celsius.

NOTE—The manufacturer shall use the appropriate value of T_k for the specified conductor material used and shall advise the user accordingly.

11.4.2.1 Reference temperature for losses and impedance

The typical reference temperature for series reactors to which losses and impedances are corrected shall be 75 °C.

NOTE—In the case of loss evaluated reactors, consideration may be given to the use of a reference temperature for loss calculations to be the average winding rise, as determined by a temperature rise test, plus 20 °C.

11.4.3 Loss measurements

11.4.3.1 General

Since many series reactors (especially high kilovoltampere units) operate at low power factors, small variations in frequency, deviations from the true sine wave in applied voltage, errors in measuring components, and electromagnetic interference may introduce significant errors in loss measurements. Proper test conditions and precision components specifically designed for low power factor measurements, are essential for an accurate determination of reactor losses.

a) Impedance bridges are frequently used to measure losses and are generally more accurate than traditional wattmeter measurements. While many configurations of impedance bridge networks are possible, the choice of a particular network shall be determined by the measurement problem at hand and the testing facilities available.[6] It should be noted that modern electronic-based wattmeters can be highly accurate.
b) If wattmeters are used to measure losses, connections to the reactor will be the same as those shown in Figure 3 for single-phase reactors and Figure 4 for three-phase stacked reactors. The total loss of a three phase stacked reactor shall be taken as the arithmetic sum of the three wattmeter readings. In the case of reactor orders with multiple three-phase stacks it is permissible to assemble only one three-phase stack and by measurement obtain the total loss. For the routine test, single-phase measurements of loss on the individual phases may be used.

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[6] See Annex E, [B4] and [B7] through [B12].

11.4.3.2 Loss tests on dry-type series reactors

In these reactors, the losses consist of the I^2R (dc resistance) losses in the conductor, the eddy losses in the conductor, and any metallic framework of the clamping structure.

Since the losses in these reactors are proportional to I^2, the losses can be measured at 100% of the rated current, or at a reduced current. In either case, precision of measurement shall be demonstrated to the purchaser's satisfaction. The losses are to be corrected to rated current and a reference temperature. In some cases, the actual average winding rise as determined by the temperature rise test plus 20°C may be used, which is an attempt to reflect actual in-service losses and actual site average ambient temperature. For three-phase stacked reactors the losses should be measured with each individual phase excited but with the reactors in three-phase configuration.

[redacted]

Figure 3—Single-Phase reactor connections for impedance-loss and impedance-voltage tests
(Instrument transformers to be added when necessary)

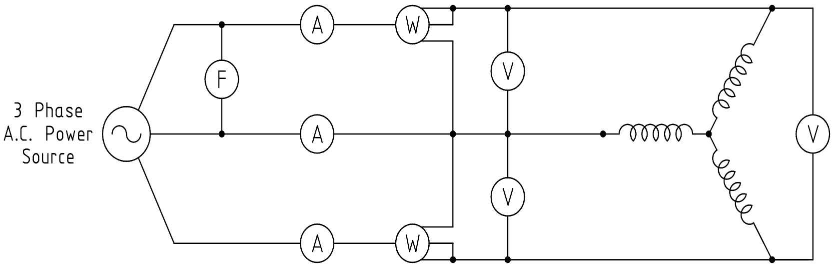


Figure 4a)—Three-Phase reactor connections for impedance-loss and impedance-voltage tests (2 watt meter method)
(Instrument transformers to be added when necessary)

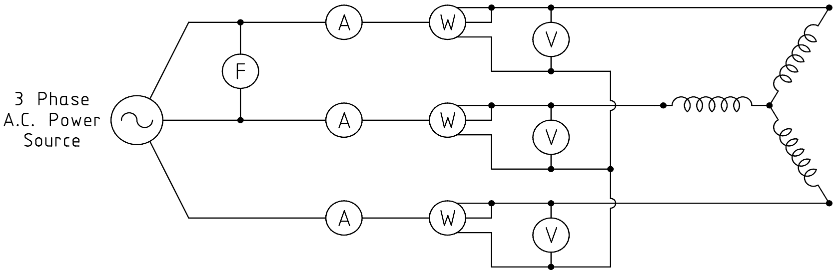


Figure 4b)—Three-Phase reactor connections for impedance-loss and impedance-voltage tests (3 watt meter method)
(Instrument transformers to be added when necessary)

11.4.3.2.1 Temperature of the winding

The temperature of the winding shall be taken immediately before and after the impedance measurements in a manner similar to that described in 11.2. The average shall be taken as the true temperature.

11.4.3.2.2 I^2R loss of the winding

The I^2R loss of the winding is calculated from the ohmic resistance measurements (corrected to the temperature at which the impedance test was made) and the currents that were used in the impedance measurement. These I^2R

losses subtracted from the impedance watts give the stray losses of the winding. When reactor windings are enclosed in shielded housings or tanks, part or all of which are magnetic material, part of the stray loss shall be considered with the winding I^2R when correcting losses from measured temperature to other temperatures. Since this varies with the proportions of the reactor design and type of shield, it will have to be approximated for each design but can be checked by measurement of loss at the start and finish of the temperature run.

11.4.3.2.3 Per-Unit values

Per-Unit values of the resistance, reactance, and impedance voltage are obtained by dividing E_r, E_x, and E_z in 11.4.1.2 by the rated voltage. Percentage values are obtained by multiplying per-unit values by 100.

11.4.4 Impedance-Loss and impedance-voltage test of a three-phase reactor

Balanced three-phase voltages of rated frequency and suitable magnitude are applied to the terminals to force rated current to circulate (see Figure 4).

11.4.4.1 Procedure

The procedure is similar to that described for single-phase units, except that all connection and measurements are three phase instead of single phase.

11.4.4.2 Line currents

If the three line currents cannot be balanced, their average rms values should correspond to the desired value.

11.4.4.3 Stray-Loss component

The stray-loss component of the impedance watts is obtained by subtracting from the latter the I^2R losses of the reactor.

11.4.4.4 Temperature correction

Temperature correction shall be made as in 11.4.2.

11.4.5 Wattmeter or bridge method

Modern electronic-based wattmeters can be highly accurate and are now typically used to measure losses. In the past, bridge methods were preferred due to their accuracy and may also continue to be used.

11.5 Temperature rise tests

11.5.1 Loading for temperature rise tests

The reactor shall be tested under loading conditions that will produce losses as close as possible to those obtained at rated frequency with rated current in the windings. If laboratory power is not sufficient or power control adjustment is not fine enough to carry out a test at rated current, testing at current levels down to 90% of rated is permissible. The measured temperature rise shall be corrected using the method in 11.5.6.

In the case of reactors to be installed in a side-by-side configuration, testing of a single unit is representative. In the case of reactors mounted in a three-phase stack configuration, they should be tested in the installed configuration with a three-phase current supply unless otherwise agreed upon between purchaser and manufacturer.

11.5.2 Temperature rise tests

11.5.2.1 General

All temperature rise tests shall be made under normal conditions of the means, or method, of cooling.

11.5.2.2 Reactor configuration

Reactors shall be completely assembled.

11.5.2.3 Ambient temperature

The ambient temperature shall be taken as that of the surrounding air, which should be preferably not less than 10 °C nor more than 40 °C. However, in recognition that it may be impractical to maintain the ambient temperature of large test laboratories within this range, temperature tests may be made with ambient temperatures outside the range specified if suitable correction factors are employed.

11.5.2.4 Ambient temperature determination

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

11.5.2.5 Minimization of errors

To reduce to a minimum the errors 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 that has a temperature 10 °C higher, or lower, than the previous steady-state indicated temperature within the container.

11.5.2.6 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 or by thermometer when required.

11.5.2.7 Temperature measuring devices

Fiber optic sensors, thermocouples, thermometers, or temperature labels may be used to measure surface temperature. It shall be noted that the use of thermocouples can be hazardous due to parts being at high voltage.

11.5.2.8 Use of initial overloads

It is permissible to shorten the time required for the test by the use of initial overloads, restricted cooling, or any other suitable method provided that the value of the thermal time constant of the reactor is not required to be determined. The thermal time constant of the reactor may also be determined during the cooling down period.

11.5.2.9 Temperature rise of the winding

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

11.5.2.10 Ultimate temperature rise

The ultimate temperature rise is considered to be reached when the temperature rise becomes constant, i.e., when temperatures measured by thermometers or thermocouples on the winding do not vary by more than 2.5% or 1 °C, whichever is greater, during a period of two consecutive hours and/or the duration of the heat run is at least five thermal time constants. (The thermal time constant shall be verified.)

11.5.3 Determination of average measured winding temperatures by the hot-resistance method

11.5.3.1 Average winding temperature rise

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

$$\theta = \frac{R}{R_o}\left(T_k + \theta_o\right) - T_k \tag{18}$$

11.5.4 Hot spot measurement

Modern dry-type air-core series 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 latter characteristic ensures winding surface temperature is measured and not cooling duct air temperature. The amount of silicone rubber sealant used is important. Sufficient material shall 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 criterion 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, can best be determined by the manufacturer due to his detailed knowledge of the product.

11.5.5 Temperature rise test in three-phase stack configuration

In the case of heat runs performed on reactors in a three-phase stack configuration, the average winding temperature rise and hot spot winding temperature rises should be obtained for each individual phase reactor. Typically, the top coil in a three-phase stack will have the highest temperature values due to the influence of the reactors in the bottom two phases.

11.5.6 Winding temperature-rise correction for reduced current

When the input test current I_t. is below the rated value of current I_r, but not less than 90% of I_r, the temperature rise $\Delta\theta_t$ of the windings, shall be measured by the resistance method when steady-state conditions have been reached, and corrected to rated load conditions $\Delta\theta_r$, by the formula

$$\Delta\theta = \Delta\theta \left[\frac{I_r}{I_t}\right]^2 \tag{19}$$

where

I_r is the rated current,
I_t is the test current,
$\Delta\theta_r$ is the average temperature rise at rated current, and
$\Delta\theta_t$ is the average temperature rise at test current.

> NOTE—The exponent of 2 used in the above calculation is conservative and is an upper bound. Typical values will range from 1.6 to 2.0. If the manufacturer uses an exponent of 2 to convert from a lower current to a higher current, then only one temperature rise test is required. If a manufacturer wishes to use an exponent lower than 2, then two temperature rise tests shall be performed to verify the actual exponent value. The determination of the exponent *n* from the test data is carried out as follows:

$$\Delta\theta = \Delta\theta \left(\frac{I_2}{I_1}\right)$$

$$\frac{\Delta\theta}{\Delta\theta} = \left(\frac{I_2}{I_1}\right)$$

$$\ln\left(\frac{\Delta\theta}{\Delta\theta}\right) = n \ln\left(\frac{I_2}{I_1}\right)$$

therefore,

$$n = \frac{\ln\left(\frac{\Delta\theta}{\Delta\theta}\right)}{\ln\left(\frac{I_2}{I_1}\right)}$$

11.5.7 Induction times

The induction time for the measuring current to become stable should be noted during the cold-resistance measurements in order to assure that sufficient time elapses for the induction effect to disappear before hot resistance readings are taken.

11.5.8 Correction of observed temperature rise for variation in altitude

11.5.8.1 Altitude not exceeding 1000 m

When tests are made at an altitude not exceeding 1000 m (3300 ft) above sea level, no altitude correction shall be applied to the temperature rise.

11.5.8.2 Reactors operating at an altitude in excess of 1000 m

When a reactor that is tested at an altitude less than 1000 m (3300 ft) is to be operated at an altitude in excess of 1000 m, it shall be assumed that the observed temperature rise will increase in accordance with the following relation:

$$\text{Increase in temperature rise at altitude A m (ft)} = \textit{observed rise} \cdot \left(\frac{A}{A_O} - 1 \right) F \tag{21}$$

where

A_0 is 1000 m (3300 ft), and
F is an empirical factor equal to 0.05.

NOTE—The "observed rise" in the foregoing equation is winding rise over the ambient temperature.

11.5.9 Correction of observed temperature rise for ambient temperature

11.5.9.1 Ambient air temperature other than 30 °C

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

$$C = \frac{T_k + 30}{T_k + \theta} \tag{22}$$

where

T_k is 234.5 for copper,
T_k is 225 for aluminum, and
θ is the ambient air temperature, in degrees Celsius.

The manufacturer shall use the appropriate value of T_k for the specified conductor material used and shall advise the user accordingly.

11.6 Short-Circuit test

11.6.1 Rationale for the short-circuit test

A short-circuit test is performed to demonstrate the ability of the dry-type air-core series reactor under test to withstand worst-case system fault scenarios. A system fault is typically composed of a full offset peak current portion and a longer duration symmetrical current portion. In most cases the offset decays to zero in under ten cycles. The high offset peak currents during the initial portion of the fault impose the highest mechanical stresses on the reactor, while the longer duration symmetrical fault current subjects the reactor to high temperatures and significant mechanical loads simultaneously.

Other system operational factors that should be taken into consideration in the specification of the short-circuit test are the number of breaker autoreclosures during a fault and the time that a fault current is allowed to flow before it is interrupted. The number of autoreclosures allowed should influence the number of mechanical peak shots performed during the mechanical short-circuit test, e.g., 1, 2, or 3. The number of cycles in each shot of the mechanical short-circuit test should reflect the utility's interrupting practice. The duration selected (typically 1, 2, or 3 s) should reflect the cumulative thermal effects of the utility's autoreclosure philosophy and the time a fault is allowed to exist before it is interrupted.

11.6.2 Basic principles of short-circuit testing

A reactor(s) may be short-circuit tested in a number of configurations. The single-phase short-circuit test may be performed on one unit or a three-phase short-circuit test may be performed on a three-phase in-line, three-phase triangular, or three-phase stacked configuration. Three-Phase reactor configurations are tested with three-phase short-circuit currents applied to the input terminals and with the output terminals connected together.

It is preferable to test the reactor(s) in a test setup that represents the installed condition as closely as possible. In this case it is important to ensure that the test is performed with components and configurations exactly as installed. Interactive forces generated by the reactor's field and current feeds (bus, cable, etc.) are an important aspect of design and any deviation in configuration or in components utilized for the test shall be fully assessed.

In most cases the reactor will not be able to be tested as installed. In these situations it is paramount to ensure that interaction force effects created by the field of the reactor and the supply circuit current are minimized. To this end the circuit setup illustrated in Figure 5 is typical of a desirable situation where interactive effects between the reactor and laboratory bus bar layout are minimized.

The objective of the short-circuit test is to demonstrate the ability of the reactor and its auxiliary components to withstand the mechanical stresses generated by internal electromagnetic forces. All forces on reactor components are the result of the interactive effects of the currents flowing in them (windings, input terminal arms) and the global magnetic field of the reactor. Forces transmitted to the reactor under test as a result of poorly restrained bus, inadequate fixing of the reactor to the test bay floor, etc., are not representative of field-installed conditions. Therefore, test setup is extremely critical to ensure realistic results.

11.6.3 Guidelines for short-circuit testing

a) Reactors should be assembled for test as closely as possible to actual service conditions. If the reactor manufacturer has included buswork or any additional parts important to the operation of the reactor, they shall be attached for the test.

   It is acceptable to test

   1) One coil of a three-phase side-by-side mounting configuration,
   2) Two coils of a two-coil stack configuration, or
   3) A three-phase stack in a three-phase configuration.

b) A minimum test current sequence consisting of one fully offset first peak and a total duration of 10 cycles shall be performed per phase.

c) Three phase stacked reactors, or a three-phase bank of separate reactors with defined installation (only when required) shall undergo three phase short circuit tests where each reactor phase shall be specifically selected to experience the first maximum offset peak current.

d) If the coil is installed in a circuit with a recloser, then three fully offset shots shall be performed (per phase for a 3 phase stack configuration) to demonstrate performance under successive reclosures.

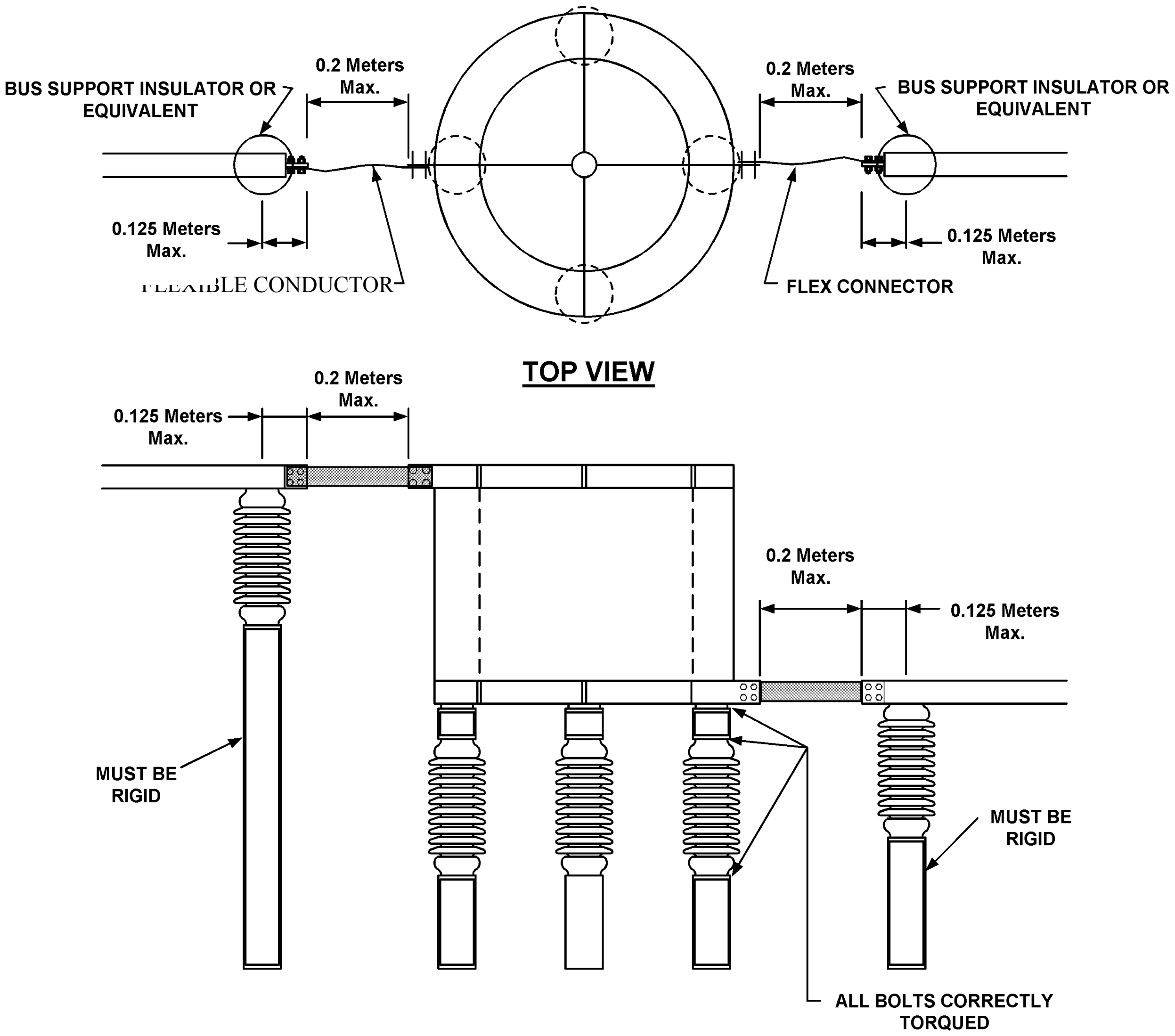
e) The thermal test, if required and not verified by calculation, shall consist of one rms symmetrical current shot for rated duration (usually 3 s) or of duration up to 6 s to give the same I^2t, if rated thermal short-circuit current magnitude cannot be achieved.

f) The end user and the reactor manufacturer shall agree on the test sequence before test.

11.6.4 Acceptance criteria

Routine tests, including measurement of inductance and losses and the performance of a turn-to-turn or impulse dielectric test, at 100% of specified voltage, shall be carried out on the reactor(s) before and after the short-circuit type test. Inductance and loss values shall be consistent within measurement tolerance limits. Oscillograms from the required dielectric test should show no change, agreeing with the limits of the high-voltage dielectric test systems.

Visual inspection of the reactor and supporting structure shall give no indication that there has been any change in mechanical condition that will impair the function of the reactor. Depending on the type of construction employed in the reactor, the areas of mechanical criticality will vary. In the case of open style reactors, focus should be on the winding-clamping system. For fully encapsulated reactors, the encapsulation should be carefully inspected for surface cracks before and after the short-circuit tests. Coating cracks at discontinuities such as at the winding-clamping system interface, etc., are not usually indications of a mechanical problem but are typically due to the inelastic nature of most paints and other coating materials. If, after the short-circuit test program, in the case of an open style reactor, the winding-clamping system has deteriorated or, in the case of an encapsulated reactor, the surface cracks have increased in number or dimension, the reactor is considered to have failed the short-circuit test. In case of doubt, up to three more short-circuit tests with fully offset current shall be applied to verify that the monitored condition has stabilized. If the deterioration continues, the reactor shall be considered to have failed the test. If conditions stabilize after one or two extra short-circuit tests and coupled with successful routine tests after short-circuit tests, the reactor shall be considered to have passed the short-circuit test.



NOTES

1—All base brackets shall be bolted to floor.

2—All bolts shall be torqued to correct value.

3—Incoming/outgoing bus connection to reactor shall be by flexible conductors links with a length of 0.2 m maximum. It is intended that the conductor links not become taut.

4—Incoming/outgoing bus shall be rigidly supported at flexible conductor links.

5—Other variations on the test set-up illustrated are acceptable providing the intent is met. Final test setup shall be fully agreed to by the manufacturer, the end user, and the test facility, or equivalent.

Figure 5—Guideline for bus connection and arrangement for short-circuit testing

11.7 Short-Time current

11.7.1 Thermal short-time current capability calculations for series (current-limiting) reactors

11.7.1.1 Increase in winding temperature

The increase in winding temperature $\Delta\theta_t$ during short-circuit conditions shall be estimated on the basis of all heat stored in the conductor material and its associated turns insulation.

11.7.1.2 Thermal capacitance

The thermal capacitance of the conductor material shall be taken as the average of the values at the starting and finishing temperatures.

11.7.1.3 Units

All temperatures are in degrees Celsius.

11.7.1.4 Appropriate calculations of increase in winding temperature

The increase in winding temperature, $\Delta\theta_t$ that will occur during a specified short-time *t* shall be calculated by the following equation:

$$\Delta\theta_t = (T_k + \theta_s)F = (T_k+\theta_s[(1 + e_s)m + 0.6\mathrm{m}^2] \tag{23}$$

where

$$F = [(1 + e_s)m + 0.6\mathrm{m}^2]$$

$$\mathrm{m} = at$$

$$a = \frac{P_s}{C_a}\,\frac{1}{T_k+\theta_{\_}} = \frac{P_r}{C_a\,(T_k + {'}5)} \tag{24}$$

where

t is the time, in seconds,

T_k is 234.5 for copper,

T_k is 225 for aluminum,

$\Delta_{\_}$ is the increase in winding temperature during time *t* (not to be greater than the difference between starting temperature θ_s and limiting temperature during short-circuit conditions given in Table 8),

θ_s is the starting temperature, and is equal to the reference ambient temperature (30 °C) plus steady-state hottest-spot temperature rise above reference ambient temperature at continuous current rating, using

a) measured hottest-spot temperature rise, if tested.

b) standard hottest-spot limiting temperature rise, if not temperature rise tested.

P_s is the short-circuit resistance loss at the starting temperature, θ_s, watts per kilogram of conductor material,

P_r is the short-circuit resistance loss at 75 °C, watts per kilogram of conductor material,

e_s is the per-unit eddy current loss, based on resistance loss at the starting temperature, and is equal to

$$e_{75}\left(\frac{T_k + 75}{T_k + \theta}\right)$$

e_{75} is the per-unit eddy current loss, based on resistance loss at 75 °C, and

C_a is the average thermal capacitance in joules (watt-second) per degree Celsius, per kilogram of conductor material, and its associated turns insulation, over the range of increase in winding temperature. The manufacturer shall use the appropriate value of T_{ic} for the specified conductor material used and shall advise the purchaser accordingly.

11.7.1.5 Thermal capacitance estimation

The thermal capacitance C_x at any temperature θ_x, below 500 °C may be closely estimated from the following empirical equations:

$$C_x = 383.6 + 0.0992\theta + 42.5\frac{Ai}{A_c}\ for\ copper \tag{25}$$

$$C_x = 892.9 + 0.4409\theta + 93.7\frac{A_i}{A_c}\ for\ \text{aluminum} \tag{26}$$

A_i is the cross-sectional area of insulation,

A_c is the cross-sectional area of conductor,

θx is the temperature in degrees Celsius, and

C_x is the thermal capacitance in joules per degree Celsius, per kilogram at temperature θ_x.

11.7.1.6 Exact calculation of increase in winding temperature

Equation (23) is an approximate formula and its use should be restricted to values of $m = 0.6$ and less. The more exact equation is as follows:

$$\Delta\theta = (T_k + \theta)\left[\sqrt{\varepsilon^{2m} + e_s(\varepsilon^{2m} - 1)} - 1\right] \tag{27}$$

ε is equal to 2.7183, which is the base of the natural logarithms.

11.8 Audible sound level test

11.8.1 General

The measurement of the sound level on dry-type air-core series reactors is an optional test. Sound level may be reported as sound pressure or sound power; as requested by the end user.

Audible sound from dry-type air-core reactors originates principally in the reactor winding where it is radiated as airborne sound. The frequency spectrum of the audible sound for a 60 Hz power system consists primarily of a tone at 120 Hz.

The A-weighted sound-pressure level measurement shall be used to determine the sound-power level of a dry-type air-core series reactor. The specified procedures for sound measurement are applicable to reactors being tested indoors or outdoors at the factory or to those that have been installed in the field.

11.8.2 Terminology

- *a)* *Sound-pressure level (L_p),* in decibels, is 20 times the logarithm to the base 10 of the ratio of the measured sound-pressure to a reference pressure of $20 \cdot 10^{-6}$ Pa.
- *b)* *Ambient sound-pressure level* is the sound-pressure level measured in the test facility without the reactor energized.
- *c)* *Measurement surface area (S)* is a hypothetical surface enveloping the sound source (reactor) and on which the measurements are taken.
- *d)* *Sound-power level (L_W),* in decibels, is 10 times the logarithm to the base 10 of the ratio of the emitted sound-power to a reference power of 10^{-12} W. It is derived from the measured sound-pressure level and the measurement surface area.
- *e)* *Semi-reverberant facility* is a room with a solid floor and an undetermined amount of sound-absorbing materials on the walls and ceiling.

11.8.3 Instrumentation

Sound-pressure level measurements shall be made with instrumentation that meets the requirements of ANSI S1.4-1983 for type 2 meters and ANSI 51.11-1986 (R1993).

A suitable wind screen on the microphone 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. Should the calibration change by more than 2 dB, the measurements shall be declared invalid. Further, it should be demonstrated prior to the measurement that the magnetic field of the reactor does not affect the reading of the sound level meter by more than 1 dB.

11.8.4 Test conditions

The reactor shall be completely assembled and the installed mounting configuration of the reactor should be utilized as much as practicable. For instance, HV series reactors are mounted on very tall structures and sound measurements on such a configuration may not be easily achievable or feasible.

Measurements should be made in an environment having an ambient sound-pressure level at least 5 dB below the combined sound-pressure level (reactor plus ambient). When the ambient sound-pressure level is 5 dB or more below the combined level of reactor and ambient, the corrections shown in Table 10 shall be applied to the combined sound-pressure level to obtain the reactor sound-pressure level. When the difference between the reactor sound-pressure level and the ambient sound-pressure level is less than 5 dB, and it is only desired to know the sound-pressure level that the reactor does not exceed, a correction of -1.6 dB may be used.

Table 10—Correction for ambient sound

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

If the reactor is tested within a semi-reverberant facility (as is usually encountered when testing indoors), an environmental correction may be applied for undesired sound reflections from the room boundaries and other reflecting objects to compensate for the increase of the measured sound level. To keep the correction as small as possible the reactor shall be located so that no acoustically reflecting surface is within 3 m (10 ft) of the measuring microphone. If a correction is applied, the validity shall be demonstrated by the manufacturer to the user. Information re the correction for a reverberant test room can be found in Clause 11.1.2 of IEC 60076-10; the IEC sound measurement test standard.

The reactor shall be energized at rated current with rated frequency. If the reactor is designed with a means for adjusting the impedance, it should be set for rated impedance.

Dry-type air core series reactors are single-phase units and shall be energized from a single-phase source. Testing of reactors in a three-phase configuration, for instance a three-phase stack, may also be possible as a special request using a three-phase supply. When available test power is insufficient for testing at rated current, then the manufacturer shall demonstrate to the user's satisfaction that reduced current testing produces sufficiently accurate results when extrapolated to the rated current level. If this cannot be demonstrated to the user, a field test can be performed.

11.8.5 Microphone positions

The reference sound-producing surface of a dry-type air-core reactor is its outside winding surface.

For single reactors with a winding less than 2.4 m (8 ft) tall, microphone locations shall be at mid-height of the winding. For single reactors greater than 2.4 m tall, microphone locations shall be at one-third and two-thirds of the winding height. For two- and three-coil stacked arrangements, microphone locations shall be at mid-height of each reactor winding. If measurements at the above heights are not possible due to bus bar layout, microphone locations shall be at the mid-height of the base reactor winding. In plan view, the microphone locations shall be laid out clockwise, sequentially at intervals of less than or equal to 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 safety requirements and minimum clearance distances to live parts.

For side-by-side arrangements of single or stacked reactors, microphone locations are determined by the same method as for a single reactor or single stack, if the locations do not overlap. If the microphone locations do overlap, measurements shall only be taken around the outermost perimeter of the resulting contour (see Figure 6).

Continuous measurement by a "walk around" test with an integrating sound level meter is the preferred test method due to the ready availability and capability of such sound level meters. The measurement contour as described in the above paragraphs is to be employed when using the capabilities of an integrating sound level meter. It is important that the contour be traversed at a near constant speed (uniform walking speed). Experience has shown that results obtained using the “walk around” audible sound measurement methodology are in agreement with those obtained using the discrete microphone position methodology.

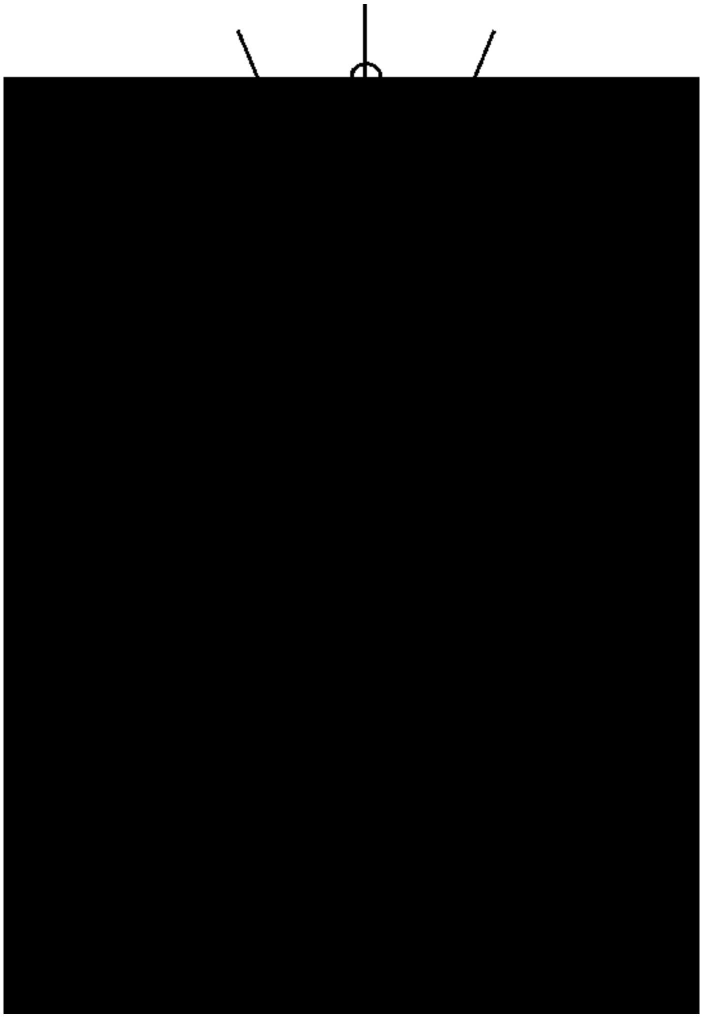


Figure 6—Microphone locations for audible sound tests

11.8.6 Sound level measurement

Sound-pressure levels shall be measured in conformance with 11.8.1, 11.8.3, 11.8.4 and 11.8.5 using the sound level meter A-weighting characteristic.

11.8.7 Calculation of average sound-pressure level

An average sound-pressure level $\overline{L}_{pA}$ shall be calculated from the measured values of the A-weighted sound-pressure level L_{pAi} by using the following equation:

$$\overline{L}_{pA} = 10\log_{10}\left(\frac{1}{N}\sum_{i=1}^{n}10^{0.1L_{pAi}}\right) \qquad (28)$$

where

$\overline{L}_{pA}$ is the average sound-pressure level in decibels (dB),

L_{pAi} is the measured sound-pressure level at location i in decibels (dB), and

N is the total number of measurement locations.

In the case of the use of an integrating sound level meter the average sound-pressure level calculated using eq. 28 is provided directly by the sound level meter.

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

a) Ambient sound-pressure level

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

11.8.8 Calculation of A-weighted sound-power level

The A-weighted sound-power level L_{WA} shall be computed as follows.

$$L_{WA} = \overline{L}_{pA} + 0\log_{10}(S) \tag{29}$$

where

L_{WA} is the A-weighted sound-power level of the reactor (dB),

$\overline{L}_{pA}$ is the A-weighted average sound-pressure level of the reactor (dB), and

S is the measurement surface area in m^2.

The measurement surface area S for a dry-type series reactor located near ground is best approximated by a hemispherical shell:

$$S = 2\pi R_m^2 \tag{30}$$

where

R_m is the measurement radius.

11.9 Seismic verification

When specified, a seismic performance verification shall be carried out using analytical methods, by testing under simulated seismic conditions, or by combined test and analysis such as that described in IEEE Std 693-2005. Although not directly applicable to electrical substation equipment, building codes such as the Uniform building Code [B13] are at times referenced regarding the seismic performance of shunt reactors.

12. Construction

12.1 Nameplates

12.1.1 Recommended information

A series reactor shall be provided with stainless steel (or equivalent) nameplate, which should include the following information:

a) Apparatus type
b) Manufacturer's name
c) Serial number (manufacturer's)
d) Year of manufacture
e) Temperature rise, °C

f) Type of cooling
g) Rated reactance
h) Measured reactance
i) Continuous current
j) Thermal _____ kA ___ s
k) Mechanical peak _____ kA
1) System frequency
m) System (or insulation) voltage rating _____kV
n) Basic impulse level _____ kV
o) Altitude ____ m ____ft above sea level (ASL,)
I)) Number and year of specification
q) Total weight ____kg ____ lb

NOTE—Total weight is the weight per phase including support elements.

12.1.2 Optional information

Optional information that may be required is as follows:

a) Voltage drop
b) Number of phases
c) Drawing number
d) Customer ID number
e) Service; indoor, outdoor

12.1.3 Mounting location

Nameplates can be mounted in any location deemed suitable by the reactor manufacturer. Some operational convenience may be realized if the nameplate is mounted such that it is readable from ground level with the use of an optical aid.

12.2 Insulator units

12.2.1 Porcelain insulator units

Porcelain insulator units shall comply with ANSI C29.9-1983 (R2002). Resin or other polymer type insulators should comply with the appropriate standards.

12.3 Tap (in a reactor)

A tap in a reactor is a connection brought out of a winding at some point between its extremities, to permit changing of the impedance.

Annex A

(normative)

Specific requirements for dry-type air-core filter reactors

A.1 General

A.1.1 Scope

The information in this annex applies to dry-type air-core reactors used in harmonic filter applications, e.g., filters with resonances in the audible frequency range. Filter reactors in ac or dc power systems are usually connected with capacitors and resistors in filter circuits, to provide a specific filter response; thus reducing harmonics by blocking or providing a low impedance path for them. This information does not apply to dc side smoothing reactors in HVDC systems.

Filter circuits are typically utilized in industrial power systems, in static VAR compensators, and in converter stations for HVDC transmission systems or HVDC back-to-back links. This information is applicable to filter reactors on both the ac and the dc sides of an HVDC power converter.

Filter reactors may be connected either in a shunt configuration with the system (shunt filters; usually the reactors are connected in series with capacitors), or in series configuration with the system, i.e., in series with the phase conductors (series filters; usually the reactors are connected in parallel with capacitors).

A.1.2 Annex precedence

Where information in this annex conflicts with that provided elsewhere in this standard, the annex information shall be considered to take precedence for dry-type air-core filter reactors.

A.2 Definitions

A.2.1 "equivalent" resistance: The value of resistance obtained by dividing total losses by the current squared at a specific frequency. The total losses do not include the active power transferred by the magnetic coupling between phases in a three-phase arrangement.

A.2.2 rated dynamic overcurrent(s): The magnitude and duration of transient currents seen by the filter reactor, such as those seen during energizing of the filter branch. The number of such dynamic overcurrents per year is critical for the design of the filter reactor.

A.2.3 rated inductance: The inductance value at rated tuning frequency. For three phase stacked filter reactors, the rated inductance per phase includes mutual coupling effects between the different phases.

A.2.4 rated power-frequency current: The rms value of power-frequency current continuously flowing through the reactor.

A.2.5 rated power-frequency voltage: The rms value of power-frequency voltage continuously applied across the reactor.

A.2.6 rated Q-factor: The ratio obtained by dividing reactance by "equivalent" resistance at rated tuning frequency and reference temperature.

NOTE—For three-phase stacked filter reactors energized with three-phase excitation, the non symmetrical mutual coupling between the different phases can cause the power loss measurement per phase to be near zero or even negative. In this case, the "equivalent" resistance to be used for Q-factor calculation includes only the DC resistance of each individual single-phase reactor plus the effective additional resistance due to stray losses but does not include the influence from mutual coupling between phases.

A.2.7 rated short-circuit current: The maximum asymmetrical peak fault current and, if applicable, maximum constant rms fault current that can be carried for a specific time by the filter reactor.

A.2.8 rated short-time current: The rms value of short-time current and its duration (if applicable) that can be seen by the filter reactor during system disturbances.

A.2.9 rated tuning frequency: The resonance frequency of the filter circuit in which the reactor is a component.

A.2.10 rated tuning-frequency current: The rms value of current of tuning frequency continuously flowing through the reactor.

NOTE—In certain special applications (audio-frequency signaling), the tuning-frequency current is intermittent. This should be taken into account in the evaluation of losses and temperature rise limits.

A.2.11 rated tuning-frequency voltage: The rms value of the tuning-frequency voltage continuously applied across the reactor.

A.2.12 mutual reactance Xm of three-phase stacked reactors: is the ratio of the induced voltage in an open phase and the current in an excited phase in Ohms per phase at a specified frequency.

A.2.13 coupling factor: is the mutual inductance between two phases of three-phase stacked reactors expressed in per unit or percentage of the square root of the product of the self inductances of the two individual phases .

NOTE—for phase 1 and 2, the coupling factor is as follows: $k = \frac{M_{12}}{\sqrt{L_1 \text{ x } L_2}}$

A.2.14 rated power frequency reactance: is the reactance at the rated frequency of the fundamental current. For three-phase stacked filter reactors, the power frequency reactance includes the mutual reactance between different phases when energized with a balanced three-phase supply.

A.3 General requirements

A.3.1 General

The steady-state voltage across a filter reactor is usually low compared to the system voltage; however, the reactor is subject to transient overvoltages. The contribution of harmonic currents through a filter reactor requires special consideration. The harmonic currents will both increase the losses in the reactor and increase the voltage across the reactor winding.

When connected in shunt configuration and in series with a capacitor, the continuous power-frequency current of the filter reactor is limited by the impedance of the series-connected capacitor. However, the harmonic current may be of the same order, or even larger than the power-frequency current, especially for double tuned filters. If the reactor is located between line and capacitor, the reactor may also be subjected to short-circuit currents due to system faults on the bus system between reactor and capacitor. The filter reactor will also be subjected to transient overcurrents during filter-switching operations and during faults on the bus to which they are connected.

When connected in series configuration with the system, the filter reactor is subjected to the system's continuous load current and currents due to system faults.

Filter reactors may also be subjected to dynamic overcurrents such as high levels of harmonics during system disturbances, such as abnormal network frequency deviations, unbalanced ac system faults, geomagnetic storms, or the energization of large system transformers.

A.3.2 Design

Filter reactors may be single-phase (side-by-side mounted) or three-phase (stacked configuration). As a result of insulation requirements between phases, the application of three-phase stacked reactors is usually confined to distribution systems class.

NOTES

1—Air-Core filter reactors are surrounded by a stray magnetic field created by the winding ampere turns. The location of the reactor relative to metallic structures should be considered with regard to inductive heating effects during normal operation, or coupled forces during short-circuit loading of the filter reactor. Furthermore, it should be noted that metallic structures, including the ground mat, may alter the reactor's inductance and Q-factor (especially three-phase stacked filter reactors).

2—In the case of three-phase configured filter reactors or filter reactors of different rating installed close to each other (or even stacked), attention should be paid to the magnetic coupling between reactors with regard to the influence on inductance and Q-factor.

3—Three-phase stacked filter reactors are mainly used in shunt-connected filter circuits. The neutral of such filter circuits is usually isolated from ground. The type of neutral treatment of the filter circuit, ungrounded or grounded, may be critical to filter performance when using stacked reactors; especially where the mutual coupling is not negligible.

Filter reactors may be designed with a means for adjusting the inductance within a limited range, usually by means of taps or by the relative movement of two “split reactance” coils. The inductance variation range is subject to agreement and shall be mentioned in the inquiry or tender.

Where variation of inductance is achieved by means of tapping, the reactor winding may be split into a main winding and a tapped winding. Inductance steps may also be achieved by tapping the main winding.

Where variation in reactance is achieved by relative coil movement, the coil is “split” into two (usually stacked) coils with adjustable separation, thus adjusting the inductance by varying the magnetic coupling between the two “split reactance” coils.

A.3.3 Design consideration for audible sound

Due to the presence of large harmonic currents that produce forced vibrations in the human audible range of the sound spectrum, the acoustic noise of filter reactors may be quite high. Filter reactors shall therefore be designed so as to avoid, as far as possible, mechanical or acoustic resonances at major audible sound frequencies.

When a filter reactor is provided with a sound mitigation enclosure, special attention shall be given to the design and manufacture of electrical connections inside the enclosure, as they cannot be inspected during operation. Fire retardant materials should be used in the sound enclosure.

A.3.4 Environmental aspects

Since the harmonic currents may cause significant voltage across a filter reactor, the environmental conditions shall be stated clearly in the inquiry, e.g., degree of salt contamination or humidity, location of site if in the tropics or close to the sea, installation in desert areas or in heavy pollution areas such as steel mills. The environmental aspects shall be considered in the design, for example, in selecting materials and dimensioning of surface and turn-to-turn stresses, to ensure safe operation during the expected lifetime of the reactor.

In addition, other environmental conditions such as actual maximum and average ambient temperatures *at the site* (vs. standard weather bureau data), seismic requirements, wind loads, etc., should be included in the reactor specification.

A.4 Ratings

Reference to 60 Hz voltages and currents apply equally to 50 Hz or other frequency power systems.

A.4.1 Voltage drop rating

The voltage drop across the reactor depends on the voltage drop due to the 60 Hz current and of all harmonic currents. The instantaneous voltage drop is a function of the magnitude of the current components and their phase relationships. The larger reactor impedance at the higher frequency components of the harmonic current can substantially increase the voltage drop.

The rated voltage drop across the reactor shall be taken as the worst-case peak voltage of the resulting voltage drop divided by $\sqrt{2}$. If the wave shape of the resulting voltage drop is unknown, the rated voltage drop is determined by the root-sum-square (rss) method using 60 Hz and harmonic frequency voltage drops, e.g.,

$$VD_{rss} = \left(\sum_{H=}^{\infty} VD_{H}{}^{2} \right)^{1/2} \qquad \text{(A.1)}$$

Where,

VD_{rss}	is the root square sum
VD_{H}	is the voltage drop at harmonic H
H	is the harmonic order

NOTE—The value of voltage drop obtained by the rss method is usually lower than the worst-case peak voltage drop but is typically the most important value necessary for the proper design of the filter reactor.

A.4.2 Current rating

Fundamental 60 Hz current, and all harmonic and dc currents where applicable, shall be specified. This is critical as they are required for both thermal and voltage design purposes. These currents constitute the current spectrum of the reactor.

NOTE—In the case of filter reactors for static VAR compensator (SVC) application, the special nature of the load should be specified and considered in the design. Intermittent current can fluctuate over a wide frequency range with interruption periods of parts of seconds to months.

A.4.3 Thermal short-time current rating

This is equivalent to the thermal short-circuit rating in accordance with 3.4.5 and 5.6.4 of this standard. For reactors in series-connected filter circuits, this value is related to system overcurrent faults.

For reactors in shunt-connected filter circuits, this value is related to temporarily increased levels of harmonic currents due to abnormal operating conditions of the harmonic source or due to detuning caused by abnormal ac network frequency deviations. The increased level of harmonics during system faults and switching events should also be considered.

Based on the system specifics of the application, the magnitude of rated short-time current shall be specified for each filter reactor rating.

A.4.4 Mechanical short-circuit current rating

This is the maximum peak current caused by any transient or short-circuit condition (see also 3.4.2 and 5.6.3 of this standard). For reactors in series-connected filter circuits, this value is related to system overcurrent faults.

For reactors in shunt-connected filter circuits, this value is usually determined by oscillations excited by faults, especially faults on the line or bus to which they are connected. Also the in-rush current during filter switching shall be considered.

The magnitude of the peak value at rated mechanical short-circuit current shall be specified in the enquiry and tender for each filter reactor and based on its individual application. For transients other than the fundamental, the time to crest shall be specified in the inquiry.

If transient currents of the same order of magnitude as the mechanical short-circuit rating are expected to be frequent, more than 10 times a year, the number of such transient current peaks per year shall be specified.

NOTE—Filter reactors used in conjunction with electric arc furnaces are, in particular, subjected to transient (dynamic) currents.

A.4.5 Rated Q-factor of a filter reactor

The rated Q-factor is the Q-factor at specified tuning frequency/frequencies, reference temperature, and the reactor's rated inductance. Unless otherwise specified, this is a guaranteed minimum value.

For three-phase stacked filter reactors, the rated Q-factor at tuning frequency is the value obtained for the individual reactor when energized with single-phase excitation.

The manufacturer shall, on request, supply information concerning the expected Q-factor of the filter reactor at specified tuning frequency/frequencies with an accuracy as defined in A.6.3.

A.4.6 Reactor duty for rating

Unless otherwise specified, the reactor duty for rating is continuous operation at rated current.

A.4.7 Limits of temperature rise for continuous rating

Limits of temperature rise for filter reactors with continuous loading shall adhere to 8.3 and Table 3 of IEEE Std C57.21-2008.

For filter reactors used in filter applications subjected to intermittent loads, Table 4 of this standard may be considered.

A.4.8 Reference temperature

The reference temperature for the filter reactor shall be the temperature rise at nominal/normal operating conditions (which may differ from the rated current) plus 20 °C. The temperature rise shall be based upon the temperature rise test or calculations made by the manufacturer when temperature rise test results are not available.

A.4.9 Insulation between phases and to ground

The insulation of a filter reactor between phases and to ground depends on the design of the filter circuit and may differ from normal insulation levels for the system. For reactors connected in shunt filters, the selection of a reduced insulation level may be appropriate. BIL and switching impulse levels between phases and to ground shall be stated in the enquiry as applicable.

The rms value of all harmonic voltages, including the fundamental and, where appropriate, the dc voltage, between the reactor and ground shall be specified, as a basis for establishing insulator creepage distance, as applicable.

A.4.10 Insulation across the coil

The insulation system of a filter reactor shall be designed to withstand both the voltage drop caused by the 60 Hz and harmonic currents, and the transient overvoltages. Depending on the filter design, the insulation levels across the reactor may be different from the insulation levels between phases and to ground. BIL and switching impulse levels across the reactor shall be included in the filter reactor specification, as applicable.

The resulting voltage appearing across the reactor during the maximum specified transient fault current shall not be greater than 83% of the rated BIL across coil.

> NOTE—When the filter reactor is protected by an arrester, the resulting voltage across the reactor during the maximum specified fault current should be lower than the SIPL (Switching Impulse Protective Level) which may be very close to the LIPL (Lightning Impulse Protective Level) of the arrester to avoid operation of the arrester during the fault. The insulation margins for the filter reactor shall be added on top of both the SIPL and the LIPL. (BIL is LIPL plus the insulation margin for LI). This is especially true for third harmonic filters for HVDC during ac network single phase ground faults. Both the BIL and the maximum resulting voltage across the reactor during the maximum specified fault current shall be specified by the purchaser. For the latter also the waveform should also be given.

A.5 Testing

A.5.1 Routine tests for filter reactors

a) Measurement of winding dc resistance
b) Measurement of inductance
c) Measurement of total losses and Q-factor
d) Lightning impulse test or turn-to-turn overvoltage test depending on the rated insulation voltage levels (see Tables 3 and 5).

A.5.2 Design tests for filter reactor

a) Temperature rise test
b) Measurement of variation of inductance and resistance with frequency
c) Measurement of self-inductances of three-phase stacked filter reactors.
d) Measurement of mutual inductances of three-phase stacked filter reactors.

A.5.3 Other tests for filter reactors

a) Thermal short-time overcurrent test or calculation
b) Mechanical short-circuit test or calculation
c) Switching impulse test to ground
d) Applied potential test
e) Chopped-Wave impulse test
f) Radio influence voltage (RIV) test
g) Audible sound test or calculation
h) Seismic verification test or calculation

A.5.4 Notes on routine tests for filter reactors

A.5.4.1 Measurement of winding dc resistance

The method of measurement is as generally outlined in 11.2 of this standard.

For tapped reactors, the dc resistance shall be measured at the nominal inductance tap.

A.5.4.2 Measurement of inductance

A.5.4.2.1 General

The inductance shall be measured on all units of an order at the rated tuning frequency only, and at all tap positions (if taps are provided) when applicable. As an option, for orders involving multiple tapped filter reactors of identical design, the inductance at each tap position must be measured on one unit of the order. For the other tapped filter reactors, of the same design, inductance shall be measured at a minimum of 3 points; typically maximum, minimum and nominal. In this case correctness of tapping shall be verified by physical inspection.

Where more than one tuning frequency is specified, (multi-tuned filters) the inductance of the filter reactor (including taps if so supplied), shall be measured at either the lowest or highest tuning frequency to be specified.

For continuously tunable filter reactors the inductance shall be measured at the nominal position and the extremes of regulation.

A.5.4.2.2 Measurement of inductance of tapped filter reactors

In some cases the value of tap step change of tapped filter reactors may be such that the measurement tolerance is of the same order of magnitude. In other words, the measurement tolerance is such that even though the tap increments physically are in uniform steps, the measured results do not reflect this fact. In most cases the problem is not the inductance/loss measurement system but is due to stray inductance in instrument connection leads and tap links. In this case one option may be to use graphical methods; manually or in the form of software embedded in the inductance/loss measurement system. Essentially the measured inductance of each tap location is graphed vs. the design turns in the tap section. A best-fit graph is generated. The inductance at the actual design turns for each tap are read off the graph and are the values reported in the test report. Large deviations between the measured inductance value at a tap location vs. the value read off the graph may indicate a manufacturing error in locating the particular tap and shall be investigated.

NOTE—It should be noted that typical practice at site during commissioning of filters is to measure the capacitance value of individual capacitor elements (“cans”), calculate the total capacitance, select the closest tap to meet design tuning and verify the appropriate tap by measuring the high frequency impedance response of the filter. Inductance of the filter reactor (at the selected tap position) is typically not measured. Therefore the exact inductance value at the various tap positions is not critical; tapping range and sufficient tap steps is, however important.

A.5.4.2.3 Measurement of inductance of three-phase stacked filter reactors

For three-phase stacked reactors the “effective inductance” (mutual inductance included) per phase shall be derived from a three-phase measurement of the reactor’s impedance by applying a system of symmetrical three-phase voltages to the star-connected phase windings with the star point floating.

The impedance for each phase shall be taken as:

$$\frac{phase-to-phase\,applied\,voltage}{\sqrt{3}\,x\,measured\,phase\,current}$$

In the case of filter reactor orders with multiple three-phase stacks it is permissible to assemble only one three-phase stack and by measurement obtain the coupling factors(s). These factors can be used to obtain the effective inductance (mutual inductance included) per phase for the other filter reactors in three-phase stack configuration from single-phase self-inductance measurements. The coupling factor between two phases is determined by measuring the mutual reactance and the self-inductances of the two phases; see A2.12 and A2.13.

NOTE—For three-phase stacked reactors, the self inductance of each individual phase is not the same as the rated and effective inductance.

NOTE—In most cases the neutral of the filters are floating. This is the case for virtually all filters in distribution class systems; either for industrial or utility networks. Most SVCs have an effectively grounded neutral. Filters for transmission class systems, including HVDC, are effectively grounded and the neutral of the filters may also be grounded. Also three-phase stacked reactors are not usually used for transmission class filters due to the insulation requirements between phases, or if they are used, then the magnetic coupling will be negligible because of the clearances. Therefore, it is justified to assume that no zero-sequence current may flow through a three-phase stacked filter reactor.

For three-phase stacked reactors, which may be subjected in service to the flow of zero sequence current, the zero-sequence inductance per phase should additionally be measured. This is done by applying a single-phase voltage to the windings of the three reactors connected in parallel and measuring the current of each phase.

A.5.4.3 Measurement of total losses and Q-factor

The method of measurement is as generally outlined in 11.4 of this standard. The losses of an air-core reactor at a given frequency are assumed to be proportional to the square of the current and may be measured at reduced current (or voltage). The Q-factor may be derived from loss and impedance test measurements as shown below.

The "equivalent" resistance shall be measured at nominal inductance at 60 Hz and at rated tuning frequencies at any convenient ambient temperature. The resistance shall be corrected to the reference temperature specified in 11.4.2 of this standard.

The inductance and the Q-factor at a specific frequency are derived from the loss and impedance test by use of the following equations:

$$L = \frac{1}{2 \cdot \pi \cdot f} \cdot \frac{E_X}{I} \tag{A.2}$$

$$Q = \frac{E_X \cdot I}{P_Z} \tag{A.3}$$

where

f is the frequency, in Hertz,
L is the inductance, in henries, at frequency f,
Q is the Q-factor at frequency f at reference temperature,
E_x is the reactance voltage, in volts (see 11.4),
I is the current, in amperes (see 11.4), and
P_z is the total losses, in watts, corrected to the reference temperature specified in 11.4.2.

NOTE—$P_z = P_r + P_s$, where P_r *is* the I^2R losses and P_s is the stray losses.

If a bridge method is employed, inductance and Q-factor at specific frequencies can be obtained directly from the measurement.

Test arrangements shall be agreed between the manufacturer and the purchaser prior to testing.

For three-phase stacked reactors, the total loss shall be measured with three-phase excitation with the reactor assembled as in service. The arithmetic sum of the measured loss of the three individual phases gives the total loss. In the case of filter reactor orders with multiple three-phase stacks it is permissible to assemble only one three-phase stack and by measurement obtain the total loss. For the routine test, single-phase measurements of loss and Q-factor on the individual phases may be used.

The measurement of the Q-factor shall be performed prior to dielectric testing and, if so specified, be repeated at the end of the test sequence.

The power-frequency winding loss is determined by measurements at power frequency. Losses for specified individual harmonic frequency components are calculated or directly obtained from measurements at the respective harmonic frequencies and added to the power-frequency loss. The total loss is referred to reference temperature.

NOTE—For filter reactors loaded with dc current, the measured dc losses, referred to the reference temperature, shall be included.

Losses shall be measured at the nominal inductance tap for tapped reactors.

A.5.4.4 Lightning impulse test

The test is as generally outlined in 11.3.6 of this standard.

The test shall be made with waves of positive polarity applied to the high-voltage terminal, with the low-voltage terminal grounded. If a specific BIL is also specified for the low voltage terminal, the impulse test or turn-to-turn test shall also be performed on the low voltage terminal, with the high voltage terminal grounded, at the prescribed low voltage terminal insulation level. For tapped reactors, the impulse or turn-to-turn test shall be performed, unless otherwise specified, at the maximum tap position on a routine test basis and at the maximum and minimum tap positions for the design test.

NOTE—If the location of the filter reactor in the filter circuit is such that it may be subjected to transient voltages from either end, then it should be impulsed from both ends. For this situation only, tapped filter reactors should be impulsed from both ends at the maximum tap position on a routine test basis and from both ends at maximum and minimum tap positions for the design test.

NOTE—All impulse tests in IEEE reactor standards are positive polarity. Positive polarity impulses provide a more onerous test on external insulation than negative polarity impulses.

A.5.5 Notes on design tests for filter reactors

A.5.5.1 Temperature rise test

The temperature rise test is carried out at power frequency. The test current shall be adjusted to produce the total fundamental plus harmonic winding losses. If the reactor is provided with an enclosure, the enclosure shall be erected for the temperature rise test. The test procedure is outlined in 11.5 of this standard.

For tapped reactors, the temperature rise test shall be performed at the maximum inductance tap. The equivalent test current is obtained from the following formula:

$$I_t^2 \cdot R_t = I_F^2 \cdot R_F + \sum_{n-2} I_{Hn}^2 \cdot R_{Hn} + \left(I_{dc}^2 \cdot R_{dc} \right) \qquad \text{(A.4)}$$

where

I_t	is the equivalent test current (50 or 60 Hz),
I_F	is the maximum continuous fundamental current,
I_{Hn}	is the maximum continuous nth harmonic current,
R_t	is the winding resistance at test current frequency corrected to maximum operating temperature,
R_F	is the winding resistance at fundamental frequency corrected to maximum operating temperature,
R_{Hn}	is the winding resistance at nth harmonic, corrected to maximum operating temperature,
m	is the highest specified harmonic,
I_{dc}	is the maximum continuous dc current if the reactor is subjected to dc current loading, and
R_{dc}	is the winding dc resistance corrected to maximum operating temperature.

Losses that do not directly influence the temperature rise of windings (e.g., losses in spiders and brackets) should not be included. However, when the reactor is provided with an enclosure, the possible effect on temperature rise due to any induced losses in the enclosure should be considered. Stray losses external to the winding and not included in the total losses to be supplied during the temperature rise test shall be defined and explained by the manufacturer for instance by using appropriate software based on magnetic field plots.

The test shall provide verification of temperature limits achieved at rated current and harmonics as described in A.4.2. Acceptable average winding and hot spot temperature shall be as specified in A.4.7.

A.5.5.2 Measurement of variation of inductance and resistance with frequency

The variation of inductance and resistance with frequency shall be measured at nominal inductance and at any convenient ambient temperature. The frequency range shall be 60 Hz to 3600 Hz for the inductance and dc to 3600 Hz for the resistance, unless otherwise specified. The measured values shall be corrected to maximum operating temperature and used for calculation of the equivalent current in A.5.5.1.

A.5.6 Notes on "other" tests for filter reactors

A.5.6.1 Inductance tap for tests

All tests in this subclause shall be performed at the maximum inductance tap.

A.5.6.2 Radio influence voltage (RIV) test

The voltage of a filter reactor to ground depends on the design of the filter circuit and may differ from the nominal system voltage. If an RIV test is specified, this fact should be considered when determining the level of the test voltage to be applied between reactor and ground for the RIV test. Normally this test applies only to filter reactors for which one terminal is directly connected to systems rated 230 kV and above.

A.5.6.3 Audible sound level test on filter reactors

A.5.6.3.1 General

Generally, an audible sound test for filter reactors shall be performed as prescribed in Section 11.8 of this standard; test setup, instrumentation, microphone positions etc.

The sound radiated from the filter reactor depends on both the power-frequency and harmonic currents. Unless otherwise specified it is recommended to consider only the most significant harmonic currents out of the harmonic current spectrum. Since simultaneous power-frequency and harmonic currents usually cannot be applied for testing, it is recommended to test the reactor successively with currents at power-frequency, significant harmonic frequencies and at frequencies which reflect the interaction of currents with different frequencies.

> NOTE--The sound level test results can then be compared with the reactor manufacturer design values. These measurements are also performed to verify the manufacturer's calculation method if it is not practicable to obtain sound level measurements at all critical specified current values and all resultant interactive values. In case of doubt regarding the final noise level performance of a filter reactor, field measurements may give a clear answer regarding audible sound performance; provided the full rated harmonic current spectrum is present.

For a reactor current spectrum with currents I1, I2, I3… the test currents (sound equivalent currents) are given as follows:

Filter Reactor Current	Amplitude of Test Current	Frequency of Test Current	Sound Frequency
I_1, I_2, I_3, ...	I_1	f_1	$2 f_1$
	I_2	f_2	$2 f_2$
	I_3	f_3	$2 f_3$
	...	…	...

For any pair of currents the following currents need to be considered due to interactive effects:

Filter Reactor Current	Amplitude of Test Current	Frequency of Test Current	Sound Frequency
I_1, I_2	$(2 * I_1 * I_2)^{1/2}$	$(f_2 + f_1)/2$	$f_2 + f_1$
	$(2 * I_1 * I_2)^{1/2}$	$(f_2 - f_1)/2$	$f_2 - f_1$

f_1, f_2, f_3.... are the frequencies of the filter reactor rms currents I_1, I_2, I_3.... that are interacting. Usually f_1 is the power frequency and f_2, f_3.... are the frequencies of the significant harmonic currents.

The harmonic power supply usually consists of a power amplifier or variable frequency inverter and associated resonant circuit elements. Rotating machines may also be used.

The A-weighted sound-pressure level measurement shall be used to determine the sound-power level of a filter reactor.

A.5.6.3.2 Test conditions

The filter reactor shall be completely assembled; including any integrated ancillary de-Q'ing components such as "de-Q'ing rings" or resistors if applicable.

The filter reactor should preferably be tested at the specified amplitudes of the harmonic currents. Nevertheless, harmonic current sources which are in use have limited power capability and most of the time, the specified harmonic current(s) cannot be fed to the reactor, the required power being in excess of the power supply capabilities. For such cases it is a general practice to perform the measurement at reduced current and correction from measured to full test currents shall be made by calculation.

If the reactor is designed with a means for adjusting the impedance, it should be set for rated impedance.

A.5.6.3.3 Sound level measurement

Sound-pressure levels shall be measured in conformance with 11.8., A.5.6.3.1 and A.5.6.3.2 using the sound level meter A-weighting characteristic.

A.5.6.3.4 Calculation of average sound-pressure level

An average sound-pressure level at each tested current and frequency value, $\overline{L}_{pA}$, shall be calculated from the measured values of the A-weighted sound pressure level L_{pAi} by using the following equation:

$$\overline{L}_{pA} = 10\log_{10}\left(\frac{1}{N}\sum_{i=1}^{n}10^{0.1L_{pAi}}\right) \qquad \text{(A.5)}$$

where

$\overline{L}_{pA}$ is the average sound-pressure level in decibels (dB),

L_{pAi} is the measured sound-pressure level at location *i* in decibels (dB), and

N is the total number of measurement locations.

In the case of the use of an integrating sound level meter the average sound-pressure level calculated using eq. A.5 is provided directly by the sound level meter.

If the test is done at reduced current, correction from measured to full test current shall be made by using the following equation:

$$\overline{L}_{pA\_corr} = \overline{L}_{pA} + 10\log_{10}\left(\frac{I_{full}}{I_{reduced}}\right) \qquad \text{(A.6)}$$

where

$\overline{L}_{pA\_corr}$ is the average sound-pressure level of the filter reactor for each individual test component, corrected to full current.

The total A-weighted sound-pressure level of the filter reactor is calculated using equation A.7:

$$L_{pA\_total} = 10\log_{10}\left(\sum_{c=1}^{n}10^{0.1\overline{L}_{pA\_corr\,c}}\right) \qquad \text{(A.7)}$$

where

L_{pA_total} is the total A-weighted sound-pressure level of the filter reactor, and

$\overline{L}_{pA\_corr\,c}$ is the sound-pressure level of each individual test component c (corrected to full current).

n is the number of harmonic frequencies of interest.

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

a) Ambient sound-pressure level

b) Acoustic characteristics of the location where sound readings are taken, e.g., reverberant properties of the test laboratory (see IEC 60076-10, clause 11.1.2).

A.5.6.3.5 Calculation of A-weighted sound-power level

The A-weighted sound-power level L_{WA} of the filter reactor shall be computed as follows.

$$L_{WA} = L_{pA\_total} + 0\log_{10}(S) \tag{A.8}$$

where

L_{WA} is the A-weighted sound-power level of the filter reactor (dB),

L_{pA_total} is the total A-weighted sound-pressure level of the filter reactor (dB), and

S is the measurement surface area in m^2.

The measurement surface area S for a dry-type air-core series reactor located near ground is best approximated by a hemispherical shell or a cylinder. The appropriate measurement surface is a function of the reactor shape (height vs diameter) and measurement distance.

Hemispherical shell:

$S = 2\pi R_m^2$

where

R_m is the measurement radius.

Cylinder (measurements made at 2 m from the surface of the reactor):

The area S of the measurement surface, expressed in square meters, is given by:

$S = (h + 2)\ l_m$

where

h is either the height in metres of the reactor

l_m is the length in metres of the prescribed contour and is calculated by $I_m = D_a + 2x)\pi$

where

D_a is the outside diameter of reactor winding x is the measurement distance from the coil outside surface

2 accounts for the top surface of the “cylinder”

NOTE—Other contours can be used if justified, such as those defined in IEC 60076-10 (2005).

A.5.6.4 Thermal short-time overcurrent test

The temperature rise at the short-time overcurrent may be obtained from a combined temperature rise test. Test sequence shall include verification that steady-state temperature for the specified continuous fundamental current and harmonics has been reached. It shall be followed by applying the specified short-time overcurrent to obtain the net resultant temperature. The acceptable hot spot temperature limit is defined in Table 4 of this standard.

As an alternative, the temperature at the specified short-time overcurrent may be calculated.

A.5.6.5 Mechanical short-circuit current test

For reactors in shunt-connected filters, the mechanical short-circuit current is not usually significant. The mechanical and thermal capabilities of filter reactors can be verified by calculation or by a suitable capacitor discharge test, based on agreement between the manufacturer and the purchaser.

A.6 Tolerances

A.6.1 Inductance

If a filter reactor is not provided with a means of adjusting the inductance, tolerances on rated inductance shall be specified and guaranteed. Where taps are specified, a tolerance for each tap should be specified or a minimum tap range and maximum tap step size should be stated.

A.6.2 Losses

The average loss of all units of the same design on one order shall not exceed the guaranteed value.

A.6.3 Q-factor

Unless otherwise specified, the "as manufactured" tolerances on Q-factor should be ±20% of the value estimated by the manufacturer.

Unless otherwise specified, the Q-factor at rated tuning frequency of any filter reactor shall not deviate from the average Q-factor of all units of the same design on one order by more than 15%.

Unless otherwise specified, the Q-factor, at the rated tuning frequency and reference temperature, measured at the end of the test sequence, shall not deviate from the one measured prior to the dielectric testing by more than 5%.

A.7 Nameplate information

A.7.1 Recommended information

The following information should be included on the nameplate:

a) Apparatus type
b) Manufacturer's name
c) Serial number
d) Year of manufacture
e) Temperature class
f) Temperature rise, °C
g) Type of cooling
h) Rated power frequency
i) Rated tuning frequency
j) Rated inductance (at rated tuning frequency)
k) Measured inductance
1) Q-factor (at rated tuning frequency) (as applicable)
m) Rated fundamental current (as applicable)
n) Rated current (rss value of all harmonic currents, including fundamental)
o) Thermal current _______ kA/_________seconds
p) Mechanical peak current________ kA
q) BIL (basic impulse insulation level)
r) Altitude (if exceeding 1000m or 3300 ft)
s) Number and year of standard
t) Total weight

A.7.2 Optional information

Optional information that may be required as follows:

a) Number of phases
b) Drawing number
c) Customer ID number
d) Service; indoor, outdoor
e) Maximum ambient temperature
f) System voltage
g) Measured inductance

A.8 Filter reactor design information

The information in the following subclauses is required to design a filter reactor properly.

A.8.1 Filter reactors for standard applications

– Maximum system voltage_______ kV
Rated system voltage ______ kV

Rated Inductance:	mH
— Tolerance:	
– Fundamental current rating:	A
– Harmonic currents, (Hz/A):	A
Short-Time current (rms symmetrical, seconds):	kA, s
Q-value at______Hz Q>____ or Q< ___or Q____±	@ *(reference temp.)* °C
– Maximum continuous voltage to ground:	kV
– Lightning impulse withstand level (LIWL)	
— Across reactor:	kV crest
— Low-Voltage terminal to ground:	kV crest
– Switching impulse withstand level (SIWL)	
— Across reactor:	kV crest
— Low-Voltage terminal to ground:	kV crest
– Mounting; side-by-side or three-coil stacked	
— Indoor or outdoor	
— Taps ______%	
— Steps ± ____	

A.8.2 Filter reactors for special applications

– Arc furnace application:	Yes/No
– Switching operations (number per year):	per year
Short-Time overcurrent	
_______Transient current (peak, duration in cycles):	kA peak, ms
_______Time constant "T" for transient current decay	s
_______ Dynamic current (peak, duration in ms):	kA peak, ms
_______Time constant "T" for dynamic current decay (T):	s
– Dynamic overvoltage (rms, duration in ms):	kV, ms
– Dynamic overvoltage time constant	s

A.8.3 Environmental conditions

— Seismic:	g
Pollution levels: salt, industrial, etc.	
- Ambient temperature (site)	
____ Annual average:	°C
____ Annual maximum:	°C
____ Annual minimum:	°C

A.9 DE-Q'ING OF FILTER REACTORS; TEST CODE IMPLICATIONS

A.9.1 INTRODUCTION

Filters are employed in a.c. power systems to prevent harmonics from entering the system or to divert them for the part of the system to be protected; as stand alone shunt filters, when they also provide capacitive reactive compensation, and as part of a static VAR system (SVC). Filters are also an important element of HVDC systems; a.c. and d.c. side filters. There are a number of shunt filter configurations; single tuned (high Q), "band pass" (low Q), high pass damped ("first order", "second order", "third order" and "C-type").

A.9.2 DE-Q'ING / DAMPING

Low Q or damping can be provided by "stand alone" resistors. In some cases resistors may be mounted on top of the filter reactor. Note that mounting the filter reactor on the resistor is not usually done due to the heat generated by the resistor. If a resistance in parallel with the reactor is required the resistor may be mounted inside the reactor; depending on the power rating of the resistor. An alternative to the parallel connected resistor may be achieved by "de-Q'ing" the filter reactor. This can be achieved by increasing the winding losses; especially over the harmonic frequencies and preferably at a selected harmonic frequency or frequencies. De-Q'ing may also be achieved by increasing the harmonic "stray losses" of the filter reactor usually by the addition of special "de-Q'ing" elements; some of which may be special patented devices such as "de-Q'ing rings".

A.9.3 TEST CODE

In the case of "stand alone resistors" there is no impact on the test code/methodology for the filter reactor. This also applies to resistors mounted on the filter reactor and connected in series with the filter reactor. Test code/methodology for the resistor and filter reactor are independent. Consideration can be made to performing temperature rise tests with the filter resistors mounted on the filter reactors to verify that reactor cooling has not been impeded and the stray magnetic field of the reactor does not adversely heat the resistor.

If a resistor is mounted in parallel with the filter reactor and is mounted inside the filter reactor then the filter reactor/parallel resistor combination shall be tested as a complete entity. The resistor shall be rated at the same BIL as the filter reactor.

In the case of de-Q'ing of the filter reactor the filter reactor shall be tested per the test code described in this document. Since de-Q'ing is passive and is based on increasing the losses (focus on harmonic losses) there is no impact on dielectric tests. There is obviously an impact on losses. Impact on temperature rise is a function of the type of de-Q'ing employed; increased winding losses vs. external de-Q'ing elements.

Where de-Q'ing accessories are fastened to the reactor these shall be included for all testing as there may be significant mechanical and thermal stresses imparted on the accessories particularly during short circuit or temperature rise testing. Also, where sound level testing is specified these tests shall be carried out with de-Q'ing accessories attached as they may contribute to the equipment sound level.

A.9.4 Conductor Insulation Temperature

If de-Q'ing is achieved in whole or in part by increasing the conductor eddy losses at specific harmonic frequencies there will be a direct correlation to conductor insulation temperature; conductor temperature rise due to de-Q'ing losses. This should be taken into consideration in determining the equivalent current for the temperature rise design/type test.

If de-Q'ing is achieved using external means such as a mounted resistor or special de-Q'ing geometry, the impact on conductor insulation temperature is secondary and also strongly geometry dependent. For instance if resistors or de-Q'ing geometries are mounted on top of or above the reactor windings the impact will be negligible. An internally mounted resistor or a resistor mounted below the reactor will contribute to a higher operating ambient and thus a higher conductor insulation system operating temperature. The temperature rise design type test shall reflect this.

If de-Q'ing is located below the reactor main winding the losses in the de-Q'ing and the associated heat generated could impact the temperature of the cooling air and the operating temperature of the reactor main winding. The rationale for the temperature rise design test shall take this into consideration.

Annex B

(normative)

Specific requirements for dry-type air-core shunt capacitor reactors

B.1 General

B.1.1 Scope

This information applies to dry-type air-core reactors used in series with shunt-connected capacitors.

Air-Core reactors are used in series with shunt-connected capacitor banks to limit in-rush currents due to capacitor bank switching, reduce out-rush currents caused by close-in faults, and to "detune" capacitor banks so as to avoid resonance with the electrical system. During normal operation the capacitor current flows through the shunt capacitor reactor. The maximum permissible (overload) current of the shunt capacitor reactor is based on the corresponding value for the capacitor bank.

Shunt capacitor reactors may be used at industrial, distribution, and transmission voltage levels and are connected to capacitor banks ranging from a few hundred kilovar to several tens of megavar.

NOTE: The terminology “shunt capacitor reactor” is used in this document as it is common practice in North America. However, in IEC 600762-10, the terminology used is “damping reactor”, although their function is in-rush or out-rush current limiting and they do not provide damping.

Additional information on shunt capacitor reactors can be found in IEEE 1036-1992.

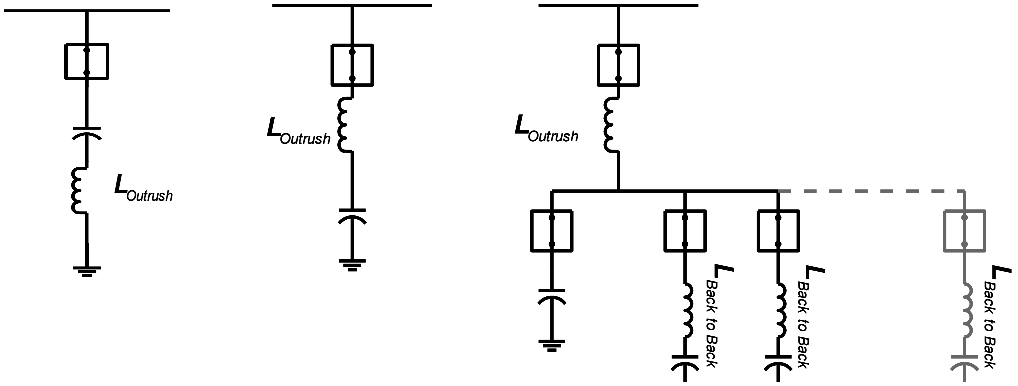


Figure B.1 Capacitor installation with single bank (left) and with multiple banks (right)

Shunt capacitor reactors shall generally comply with the requirements given in IEEE Std 18-2002.[7]

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[7] For information about references in this annex, see B.1.3.

B.1.2 Annex precedence

Where information in the annex conflicts with that provided elsewhere in the standard, the annex information shall take precedence for the respective reactor type.

B.1.3 References

This annex shall be used in conjunction with the following publications, where applicable.

ANSI C37.06-2009, American National Standard for Switchgear—AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis—Preferred Ratings and Related Required Capabilities.

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

IEC 60871-1, Shunt Capacitors for Power Systems.

IEEE Std. 18-2002, IEEE Standard for Shunt Power Capacitors (ANSI).

IEEE 1036-1992, Guide for the Application of Shunt Power Capacitors.

IEEE C57.21-2008, IEEE Standard Requirements, Terminology, and Test Code for Shunt Reactors Rated Over 500 kVA (ANSI).

NEMA CP1 – 2000 (R2008) Shunt Capacitors.

B.2 Definitions

B.2.1 "effective" resistance: The value of resistance obtained by dividing total losses by the current squared at a specific frequency.

B.2.2 Q-factor: The ratio of reactance to "effective" resistance at specified transient in-rush frequency and reference temperature.

B.2.3 rated continuous current: The effective root-mean-square (rms) value of power-frequency current (including the effect of continuous overvoltage, capacitor tolerance, and harmonics) that can be carried by the reactor for the duty specified without exceeding the specified temperature limits, and within the limits of established standards.

B.2.4 rated inductance: The inductance value of the shunt capacitor reactor that will provide the required reduction of transient in-rush current at the specified frequency.

B.2.5 rated transient in-rush (or out-rush) current: The peak value of the highest transient in-rush, or out-rush, current at the specified frequency that the shunt capacitor reactor is capable of withstanding with no loss of electrical or mechanical integrity.

B.2.6 rated transient in-rush (or out-rush) frequency: The resonant frequency of the shunt capacitor reactor, associated shunt capacitor bank, and relevant parts of the system for the operating conditions of capacitor bank switching or worst-case "close in" fault.

B.3 General requirements

B.3.1 General

The steady-state voltage across a shunt capacitor reactor is usually low compared to the system voltage. However, shunt capacitor reactors are usually switched very frequently, often several times per day, and subject to routine transient overvoltages. Also, the presence of harmonic currents through a shunt capacitor reactor requires special consideration as the harmonic currents will both increase the losses in the reactor and increase the voltage drop across the reactor winding.

A shunt capacitor reactor is subject to in-rush current transients due to switching operations and out-rush transient currents due to close-in faults. If the reactor is arranged between line and capacitor, the reactor may also be subject to short-circuit currents due to faults on the bus between reactor and capacitor.

Therefore, a complete specification for shunt capacitor reactors should include, as applicable, specifics on switching duty; symmetrical short-circuit current duration and magnitude; asymmetrical (peak) short-circuit current; and maximum transient in-rush and out-rush current magnitude, frequency, and duration.

Care should be taken to understand Transient Recovery Voltages (TRV) for circuit breakers applied in conjunction with shunt capacitor banks and reactors. Annex F contains additional background information.

B.3.2 Design

Shunt capacitor reactors for in-rush/out-rush current limitation are normally single-phase units applied in three-phase sets and are normally not tapped. They may be mounted in any conventional configuration, but are usually arranged in a side-by-side or three-phase vertical stacked arrangement.

B.3.3 Design considerations for harmonics

The impedance of a shunt capacitor decreases with higher frequency and can result in significant harmonic frequency content in a shunt capacitor bank's current. This characteristic is considered in applicable standards for shunt power capacitors. It also must be noted that the impedance of the shunt capacitor reactor increases with higher frequency. Therefore, the harmonic currents of higher frequencies are more pronounced in the shunt capacitor bank current spectrum than the corresponding harmonic voltages in the system voltage spectrum.

The following items should be considered:

1— Worldwide the harmonic contamination of the ac systems is increasing. Past “rules of thumb” may not be sufficient.

2—This standard provides general guidelines, but the purchaser shall consider actual circuit configurations regarding the risk for higher harmonic content.

3—The general guidelines can be significantly higher for grounded capacitor banks than for ungrounded capacitor banks. The reason is that grounded capacitor banks are stressed by the transformer excitation current (3^{rd}, 9^{th}, 15^{th} zero sequence harmonic etc.). The harmonics of the transformer excitation current increase with system voltages and are the worst at the highest overvoltages.

The relations are demonstrated by the following formulas, which are valid for harmonics of frequency below the resonance frequency of the shunt capacitor and the shunt capacitor reactor. These are normally the harmonics of interest.

$$THD = \sqrt{\sum \left(\frac{V_h}{V_1} \right)^2} \times 00 \qquad \text{(B.1)}$$

$$F_{hI} = \sqrt{1 + \sum \left(\frac{h \cdot V_h}{V_1} \right)} \qquad \text{(B.2)}$$

$$F_{hV} = \sqrt{1 + \sum \left(\frac{h^2 \cdot V_h}{V_1} \right)} \qquad \text{(B.3)}$$

where

THD is the total harmonic distortion (%) of the ac bus voltage,
F_{hI} is the harmonic current distortion factor of the shunt capacitor bank current,
F_{hV} is the harmonic voltage distortion factor of the shunt capacitor reactor voltage,
V_1 is the fundamental voltage of the ac bus,
V_h is the harmonic voltage of the ac bus, and
h is the harmonic order.

The continuous current for shunt capacitor reactors can be calculated from the following formulas:

$$I_{1N} = \frac{MVA_r \times 1000}{\sqrt{3} \times V_s} \qquad \text{(B.4)}$$

$$I_{eff} = I_{1N} \cdot F_v \cdot F_t \cdot F_{hI} \qquad \text{(B.5)}$$

where

I_{1N} is the nominal fundamental current in kiloamperes,
MVA_r is the nominal three-phase rating of capacitor bank (at nominal ac voltage),
V_s is the nominal line-to-line system voltage in kilovolts,
I_{eff} is the effective (rated) rms current of the shunt capacitor reactor,
F_v is the voltage factor; ratio between maximum system rms voltage and nominal system rms voltage,
F_t is the capacitance tolerance factor for the shunt capacitor rating in per-units, and
F_{hI} is defined above.

It shall be considered that due to the low impedance of the shunt capacitor bank, the content of high order harmonics on the ac bus normally is reduced, and that for high-order harmonics the impedance of the shunt capacitor reactor will be significant. In addition, with the shunt capacitor bank connected, there are significant ac bus harmonic voltages of frequencies at or above the resonance frequency, the continuous harmonic loading of the shunt capacitor reactor may be significant. Then Annex A of this standard may be more applicable.

Based on the above, a few guidelines for establishing the "effective" current rating of the shunt capacitor reactor are offered for capacitors manufactured according to ANSI and IEEE standards:

F_v is typically 1.05 but could be larger. Overvoltages are limited to 110% of rated “can” voltage.

F_t is normally 1.10, capacitor can tolerance is -0 to +10%, but overall bank tolerance is usually less. The capacitor manufacturer should be consulted re bank tolerances.

F_{hI} should be at least 1.075 for an ungrounded capacitor bank, or at least 1.18 for a grounded capacitor bank.

Therefore, the guideline for an ungrounded capacitor bank is

$$I_{eff} = I_1 \cdot (1.1 \cdot 1.10 \cdot 1.075) = I_1 \cdot 1.24 \tag{B.6}$$

Similarly, the guideline for a grounded capacitor bank is

$$I_{eff} = I_1 \cdot (1.1 \cdot 1.10 \cdot 1.18) = I_1 \cdot 1.36 \qquad \text{(Note capacitors are limited to 1.35)} \tag{B.7}$$

It is important to note that all devices utilized for the capacitor bank design shall be selected in consideration of the above “effective current” ratings.

It shall be emphasized that the above are general guidelines and the purchaser shall review the situations regarding highest continuous system voltage, capacitor bank tolerances and the expected future harmonic distortion. If future conditions are expected to be worse than the general figures given in this standard, the relevant information shall be included in the specification.

B.3.4 Design considerations for in-rush frequency

Due to the repetitive nature of the in-rush duty, the reactor should not have mechanical resonances close to twice the in-rush frequency. The frequency band for the in-rush frequency due to different shunt capacitor bank(s) and system operating configurations shall be specified, if it exceeds ±2%.

B.4 Ratings

Reference to 60 Hz voltages and currents apply equally to 50 Hz or other power system operating frequencies.

B.4.1 Rated continuous current

The rated continuous current of the shunt capacitor reactor shall be selected to be at least equal to the maximum permissible continuous current of the associated capacitor bank or the effective (rated) current as calculated above, whichever is greater. This current should be specified in the inquiry.

NOTES

1—As specified in 5.3 of IEEE Std 18-2002, the allowed occasional rms current through a shunt capacitor bank is 1.35 times the normal fundamental current, provided that $F_y = 1.1$ is not exceeded and capacitors are designed to operate up to 135% of rated kilovars, including the kilovars due to fundamental voltage and to all harmonic voltages.

2—Capacitor “can” capacitance tolerances specified in IEEE Std. 18-2002 are – 0% to + 10%, implying a tolerance factor F_t of 1.10; however, overall bank tolerances can be less. See Clause B.3.3.

B.4.2 Overload current rating

The maximum permissible overload current of the shunt capacitor reactor is based on the corresponding value for the capacitor bank as determined by system operating conditions and information in IEEE Std. 18-2002, IEEE 1036 and NEMA CP 1-2000 (R2008).

> NOTE—For special capacitor applications, such as static VAR systems or HVDC systems, the overload currents as specified in power capacitor standards are not always applicable.

B.4.3 Rated transient in-rush current

This is the highest transient in-rush current covering all recognized cases of regular capacitor bank or bank section switching (including out-rush during close-in faults). The relevant transient in-rush resonant frequency shall be specified in the inquiry. The manufacturer shall, upon request, supply information about the expected Q-factor of the shunt capacitor reactor at this frequency with an accuracy as defined in B.6.2. The shunt capacitor reactor shall be capable of withstanding the dynamic effects of this rated transient in-rush current.

B.4.3.1 Transient in-rush considerations

The following should be considered:

a) The thermal effect of the transient in-rush current is normally not significant.

b) If the shunt capacitor reactor is required to withstand contingency overcurrents in excess of the rated transient in-rush current, for example due to close-in bus faults, the magnitude and duration of such overcurrents shall be specified.

c) Acceptable limits for capacitive transient in-rush current and frequency for breaker closing are defined in Tables 1A, 2A, and 3A, "Preferred Capacitive Current Switching Ratings," of ANSI C37.06-2000.

B.4.4 Voltage rating

The power-frequency voltage drop is equal to the reactor rated current multiplied by the reactor impedance at power frequency. However, a shunt capacitor reactor shall be able to operate continuously with a much higher voltage across the reactor due to the presence of harmonics. Unless otherwise specified, the shunt capacitor reactor shall be rated for a continuous voltage across the reactor that is five times the fundamental voltage drop. (This means a value of five for the harmonic voltage distortion factor F_hu, as defined in B.3.3, is assumed).

The maximum transient in-rush or out-rush peak voltage across the reactor shall be specified.

B.4.5 Reactor duty for rating

Unless otherwise specified, the reactor duty for rating is continuous operation at rated current.

The estimated repetition rate of transient in-rush or out-rush current events shall be specified in the inquiry as the number of events per day or the number of events per year.

NOTES

1—For special capacitor applications, such as in static VAR systems, the shunt capacitor bank may be subjected to intermittent duty.

2—Transient overvoltage and overcurrent events for shunt capacitor banks are defined in 5.8 of IEEE Std 18-2002. Additional information can be found in IEEE 1036 and NEMA CP 1-2000 (R 2008).

B.4.6 Limits of temperature rise for continuous rating

For reactors with intermittent loading, Table 4 of this standard may be used. However, where reactors are specified to be energized continuously, limits of temperature rise for shunt capacitor reactors shall be as specified in 8.3 and Table 3 of IEEE Std C57.21-2008.

B.4.7 Insulation level

Unless otherwise specified, the insulation level shall correspond to the highest voltage level for equipment on the system in which the shunt capacitor reactor is to be installed. If one terminal of the shunt capacitor reactor is intended to be directly grounded, non-uniform insulation may be applied by agreement between the manufacturer and the purchaser. BIL and switching impulse levels across the reactor and to ground shall be specified in the inquiry as applicable. The BIL levels shall be selected from the standard values in Table 5.

The rms value of all harmonic voltages, including the fundamental voltage, between the reactor and ground or between phases (for stacked reactors) shall be specified as a basis for establishing insulator creepage distance, as applicable.

B.5 Testing

B.5.1 Routine tests for shunt capacitor reactors

a) Measurement of winding dc resistance
b) Measurement of inductance
c) Measurement of losses and Q-factor
d) Lightning impulse test or turn-to-turn overvoltage test depending on reactor voltage class (see Tables 3 and 5).

B.5.2 Design tests for shunt capacitor reactors

— Temperature rise test

B.5.3 Other tests for shunt capacitor reactors

a) Thermal short-time overcurrent test or calculation
b) Mechanical short-circuit test or calculation
c) In-Rush current withstand test or calculation
d) Chopped-Wave impulse test
e) Audible sound test or calculation
f) Seismic verification test or calculation
g) Mechanical resonance test or calculation

B.5.4 Notes on routine test for shunt capacitor reactors

B.5.4.1 Measurement of winding dc resistance

The method of measurement is as generally outlined in 11.2 of this standard.

B.5.4.2 Measurement of inductance

The inductance shall be measured at 60 Hz and at transient in-rush frequencies at any convenient ambient temperature.

B.5.4.3 Measurement of losses and Q-factor

The method of measurement is as generally outlined in 11.4 of this standard. The losses of an air-core reactor are assumed to be proportional to the square of the current and may be measured with reduced current (or voltage). The Q-factor may be derived from loss and impedance test measurements as shown below. At high harmonic frequencies the test arrangement should be validated for high-frequency performance to ensure that the impedance of the connections does not contribute to errors in the measurements.

The "effective" resistance shall be measured at rated transient in-rush frequency at any convenient ambient temperature. The resistance shall be corrected to the reference temperature specified in 11.4.2 of this standard.

The loss and impedance test shall be carried out at the fundamental frequency and/or the in-rush frequency.

The inductance and the Q-factor at a specific frequency are derived from the loss and impedance test by use of the following equations:

$$L = \frac{1}{2 \cdot \pi \cdot f} \cdot \frac{E_x}{I} \tag{B.8}$$

$$Q = \frac{E_x \cdot I}{P_z} \tag{B.9}$$

where

f	is the frequency, in Hertz,
L	is the inductance, in henries, at frequency f,
Q	is the Q-factor at frequency f,
E_x	is the reactance voltage, in volts at frequency f (see 11.4),
I	is the current, in amperes, at frequency f (see 11.4), and
P_z	is the total losses, in watts, at frequency f corrected to the reference temperature specified in 11.4.2.

NOTE—$Pz_z = P_{rr} + P_s$ where P_r is the I^2R losses and P_s is the stray losses.

If a bridge method is employed, inductance and Q-factor at specific frequencies can be obtained directly from this measurement.

Test arrangements shall be agreed to between the manufacturer and the purchaser prior to testing.

The measurement of the Q-factor shall be performed prior to dielectric testing and, if so specified, shall be repeated at the end of the test sequence.

Losses are referred to rated current at power frequency.

B.5.4.4 Lightning impulse test

The test is as generally outlined in 11.3.6 of this standard.

The test shall be made with positive polarity applied to each terminal with the other terminal grounded. For cases where the reactor is located between the low voltage part of the capacitor bank and the ground, the impulse shall be applied to the high-voltage terminal (based on the installed configuration) with the low-voltage terminal grounded. In such a case, if the low voltage terminal also has a rated lightning impulse specified (value may be different), the test shall also be performed on the low voltage terminal with the high voltage terminal grounded.

B.5.5 Notes on design tests for shunt capacitor reactors

B.5.5.1 Temperature rise test

The temperature rise test is carried out at power frequency as specified in 11.5 of this standard. Limits for temperature rise are specified in B.4.6.

B.5.6 Notes on "other tests" for shunt capacitor reactors

B.5.6.1 Mechanical short-circuit test

For shunt capacitor reactors, the mechanical short-circuit test may be carried out at power frequency in accordance with 11.6.2, 11.6.3, and 11.6.4 of this standard. As an alternative, the short-circuit capability may be verified by calculation.

B.5.6.2 Transient in-rush (or out-rush) current withstand test

For shunt capacitor reactors, the transient in-rush current requirement is usually (except for some back-to-back switching applications) lower in magnitude than the power-frequency fault current requirement and thus may be easily verified by calculation.

B.5.6.3 Mechanical resonance test

Due to the repetitive nature of the in-rush duty, consideration should be given to performing a test to demonstrate that the mechanical resonances of the winding are at least 10% away from a value of twice the in-rush current frequency. The manufacturer shall propose a suitable test procedure. As an alternative, this may be verified by calculation.

B.6 Tolerances

B.6.1 Inductance

The inductance is +20/-0% of rated inductance or as specified.

B.6.2 Q-Factor

Unless otherwise specified, the tolerance on Q-factor shall be ±20% of the value estimated by the manufacturer.

Unless otherwise specified, the Q-factor, at the in-rush frequency and reference temperature, measured at the end of the test sequence, shall not deviate from the one measured prior to the dielectric testing by more than 3%.

B.7 Nameplate information

B.7.1 Recommended information

The following information should be included on the nameplate:

a) Apparatus type
b) Manufacturer's name
c) Serial number
d) Year of manufacture
e) Thermal class of insulation
f) Temperature rise, °C
g) Type of cooling
h) Rated power frequency
i) Rated inductance (at rated in-rush/out-rush frequency)
j) Measured inductance
k) Rated continuous current
1) Mechanical peak current ________kA
m) Voltage drop
n) BIL (basic impulse insulation level)
o) Altitude
I)) Number and year of specification
q) Number of this standard
r) Total weight

B.7.2 Optional information

Optional information that may be required is as follows:

a) Number of phases
b) Drawing number
c) Customer ID number
d) Service; indoor, outdoor
e) Maximum ambient temperature
f) System voltage
g) Thermal current kA _______
h) In-Rush frequency
i) Q-Factor (at transient in-rush frequency)

Annex C

(normative)

Specific requirements for dry-type air-core discharge current-limiting reactors for series capacitor bank applications

C.1 General

C.1.1 Scope

This information applies to dry-type air-core discharge current-limiting reactors used in the bypass/discharge circuit of high-voltage series compensation capacitor bank applications.

Discharge current-limiting reactors are usually integral components of distribution and transmission voltage level series capacitor banks. Basically they are installed to limit the capacitor discharge current when the series capacitor bank bypass gap sparks over or the bypass switch closes.

The information is not directly applicable to reactors applied in series with a thyristor switch in controllable series capacitor applications. For such reactors, the information in this annex regarding short-circuit and discharge current rating is applicable, while Annex A (for filter reactors) may be more appropriate for other design and performance characteristics.

C.1.2 Annex precedence

Where information in the annex conflicts with that provided elsewhere in the standard, the annex information shall take precedence for the respective reactor type.

C.1.3 Supporting Documentation

This annex shall be used in conjunction with the following publications, as appropriate:

IEC 143-1-2004, Series capacitors for power systems—Part 1: General—Performance, testing and rating—Safety requirements—Guide for installation.

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

IEEE Std 824-2004, IEEE Standard for Series Capacitors in Power Systems (ANSI).

C.2 Definitions

C.2.1 discharge frequency: The resonant frequency of the discharge current-limiting reactor and associated series capacitor bank at capacitor bank discharge due to breaker closing or spark gap ignition.

C.2.2 Q-factor: The ratio between reactance and resistance at specified discharge frequency and reference temperature.

C.2.3 rated continuous current: The rms value of power-frequency current continuously flowing through the reactor (including harmonics).

C.2.4 rated discharge current: The peak value of the highest discharge current specified for the discharge current-limiting reactor mechanical design (including power-frequency fault current).

C.2.5 rated inductance: The inductance value at power frequency specified for the discharge current-limiting reactor.

C.3 General requirements

C.3.1 General

Typical one-line diagrams for a series capacitor bank with discharge current-limiting reactor are shown in Figure C.1. Normally the bypass switch is open and the line current flows through the capacitors. For this condition there is no current through, and no voltage across, the reactor. However, when the bypass switch is in the closed position, current can flow in the discharge current-limiting reactor for extended periods of time. At the frequency of the power system, the reactance of the reactor is much less than that of the capacitor. Hence, during the bypassed condition, the current in the reactor is almost the same as the line current. Under this condition, the reactor will be exposed in full measure to power system fault currents. However, transient voltages across the reactor are limited by the capacitors, gaps, and metal oxide varistor(s) ("MOV"s) that are electrically in parallel with the reactor under this bypassed condition.

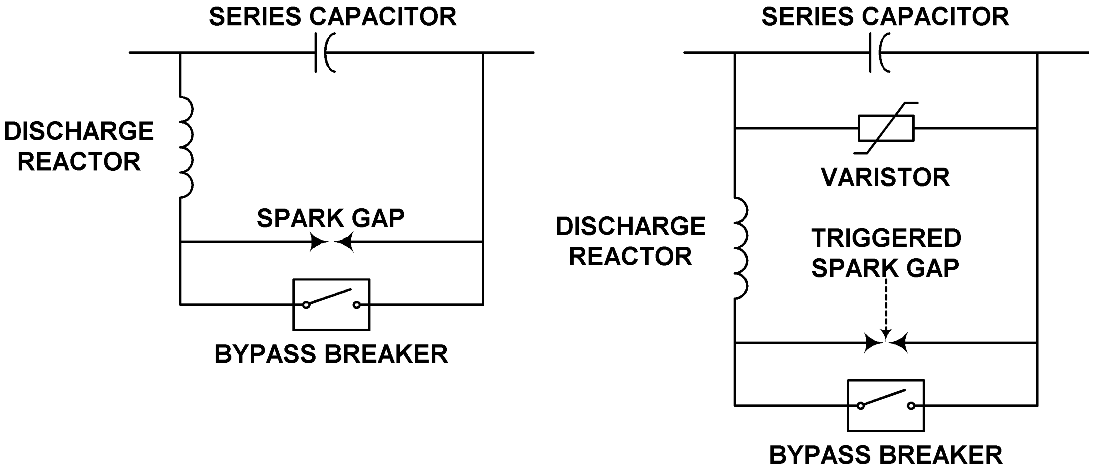


Figure C.1—Typical configurations for a series compensation capacitor with discharge current-limiting reactor

Discharge current-limiting reactors shall be designed to withstand system power-frequency fault currents and higher frequency capacitor discharge current. Since the spark gap is ignited or the breaker is closed under conditions of short-circuit current through the series capacitor bank, the maximum discharge current peak consists of the capacitive discharge current superimposed upon the power-frequency fault current. The maximum total peak current for a discharge current-limiting reactor shall be specified as well as the damping factor for the discharge current.

When the series capacitor is bypassed, the reactor/capacitor combination forms a parallel resonance circuit. It is suggested that the selection of the inductance, the permissible manufacturing tolerance for that inductance, and the harmonic current rating of the reactor take into account the harmonic current in the line and the possible amplification of that current caused by the interaction of the paralleled reactor/capacitor combination with the system.

In some cases, the discharge damping circuit may be designed with a reactor of low Q-factor at the discharge frequency or utilize a damping resistor in parallel with the reactor. The function of the resistor is to quickly damp the capacitor discharge current. The discharge damping reactor is equipped with a series connected device (spark gap or "MOV") that will "electrically" connect the resistor in the discharge circuit only during capacitor discharge mode to minimize power losses in normal by-pass conditions.

C.3.2 Design

Discharge current-limiting reactors are single-phase units usually mounted on a high-voltage elevated platform with the series capacitors. The platform is mounted on insulators to provide full phase insulation to ground. Therefore, the impulse rating of the reactor to the platform (potential) is much lower than system phase-to-ground requirements. Also, a metal oxide varistor is usually connected in the bypass circuit with the reactor to limit the voltage across the capacitor and reactor. Discharge current-limiting reactors are normally not tapped.

C.3.3 Corona shielding

Normally the discharge current-limiting reactors are shielded from full phase-to-ground voltage exposure by the platform. However, if the reactor is located at the outer edge of the platform or outside the platform, corona shielding may be needed. The requirement for corona shielding due to exposure to the full phase-to-ground voltage shall be specified, if applicable.

C.3.4 Discharge frequency considerations

Due to the repetitive nature of the discharge duty, the reactor should not have mechanical resonances close to twice the discharge frequency. The frequency band for the discharge frequency due to different configurations of the series compensation arrangement shall be specified. Also, the expected frequency range and magnitude of discharge currents due to different operating configurations of the series compensation capacitor bank shall be specified when applicable.

C.4 Ratings

Reference to 60 Hz voltages and currents apply equally to 50 Hz or other frequency power systems.

C.4.1 Rated continuous current

The rated continuous current of the discharge current-limiting reactor is the current that can be carried by the reactor when operating for the duty specified as a series element in the transmission line without exceeding the temperature limits and within the limits of established standards.

C.4.2 Thermal short-time current rating

The thermal short-time current rating is determined as specified in 3.4.5 and 5.6.4 of this standard.

C.4.3 Rated discharge current (peak value)

The rated discharge current is the highest discharge current covering all recognized cases of discharge of the series capacitor bank as a consequence of power-frequency fault current. The high-frequency capacitor discharge current will be superimposed on the power-frequency fault current. The peak currents should be added together to determine the worst-case peak current duty for the discharge current-limiting reactor unless more accurate system information is available. With modern protection schemes, the actual peak current is lower than the arithmetic sum. The relevant discharge resonant frequency shall be specified. The manufacturer shall, upon request, supply information about the expected Q-factor of the discharge current-limiting reactor at this frequency. The discharge current-limiting reactor shall be capable of withstanding the dynamic effects of this rated discharge current.

NOTES

1—The thermal effect of the discharge current is normally not significant for the reactor.

2—The peaks of the capacitor discharge current and the fundamental frequency fault current do not normally coincide.

3—In the case where a damping resistor is used in the discharge damping circuit, the discharge frequency may be a different value depending on whether the resistor is connected or not. However the difference in frequency if the resistance is connected or not is usually very small.

C.4.4 Voltage rating

The power-frequency voltage drop is equal to the reactor rated current multiplied by the reactor impedance at power frequency.

The maximum discharge peak voltage across the reactor shall be specified.

C.4.5 Q-Factor

When the damping of the discharge current is determined by the losses of the discharge current-limiting reactor, a maximum Q-factor at the discharge frequency may be specified. Under these conditions, the decay of the capacitor discharge current is governed by the Q-factor of the reactor at the discharge frequency and thus the time constant of the discharge current decay is $2L/R_f$. The time constant of the decay of the capacitor discharge current should not be confused with the reactor time constant, which is L/R_f.

C.4.6 Reactor duty for rating

Subclauses 3.5 and 8.1.4 of this standard apply.

The estimated frequency of discharge current events shall be specified as the number of events per day or number of events per year.

C.4.7 Insulation level

The insulation of the discharge current-limiting reactor depends on the insulation coordination for the series capacitor arrangement. The maximum voltage on the capacitor at time of "gap sparkover" or switch closure should be specified. BIL and switching impulse levels across the reactor and to platform (potential) shall be specified as applicable. The BIL level may be selected from the standard values in Table 5 in this standard but customized or adapted values may also be used. The rms value of all harmonic voltages, including the fundamental voltage, between the reactor and platform (potential), shall be specified as a basis for insulator creepage distance, as applicable.

C.5 Testing

C.5.1 Routine tests for discharge current-limiting reactors

a) Measurement of winding dc resistance
b) Measurement of inductance
c) Measurements of losses and Q-factor
d) Lightning impulse test or turn-to-turn overvoltage test depending on reactor lightning impulse level (See Tables 3 and 5 in the standard.)

C.5.2 Design tests for discharge current-limiting reactors

a) Temperature rise test
b) Discharge current test
c) Fault-Current test
d) Modified short-circuit test (mechanical short-circuit/discharge current test and thermal short-circuit test)

NOTE—Item d) is an alternative to b) and c).

C.5.3 Other tests for discharge current-limiting reactors

a) Seismic verification test or calculation
b) Mechanical resonance test

C.5.4 Notes on routine tests for discharge current-limiting reactors

C.5.4.1 Measurement of winding de resistance

The method of measurement is as generally outlined in 11.2 of this standard.

C.5.4.2 Measurement of inductance

The inductance shall be measured at power frequency and at discharge frequencies at any convenient ambient temperature.

C.5.4.3 Measurement of losses and Q-factor

The method of measurement is as generally outlined in 11.4 of this standard. The losses of an air-core reactor are assumed to be proportional to the square of the current and may be measured at reduced current (or voltage). The Q-factor may be derived from loss and impedance measurements as shown below. At high frequencies, the test arrangement should be validated for high-frequency performance to demonstrate that the impedance of the connections does not contribute to errors in the measurements. Losses are referred to rated current at power frequency.

The resistance shall be measured at discharge frequency at any convenient ambient temperature. The resistance shall be corrected to the reference temperature specified in 11.4.2 of this standard.

The inductance and the Q-factor at a specific frequency are derived from the loss and impedance test by use of the following equations:

$$L = \frac{1}{2 \cdot \pi \cdot f} \cdot \frac{E_x}{I} \qquad \text{(C.1)}$$

$$Q = \frac{E_x \cdot I}{P_z} \qquad \text{(C.2)}$$

where

f is the frequency, in Hertz,
L is the inductance, in henries, at frequency f,
Q is the Q-factor at frequency f,
E_x is the reactance voltage, in volts at frequency f (see 11.4),
I is the current, in amperes at frequency f (see 11.4), and
P_z is the total losses, in watts at frequency f, corrected to the reference temperature specified in 11.4.2.

NOTE—$P_z = P_r + P_s$ where P_r is the I^2R losses and P_s is the stray losses.

Test arrangements shall be agreed to between the manufacturer and the purchaser prior to testing.

The measurement of the Q-factor shall be performed prior to dielectric testing and, if so specified, be repeated at the end of the test sequence.

C.5.4.4 Lightning impulse test

The test is generally outlined in 11.3.6 of this standard.

C.5.5 Notes on design tests for discharge current-limiting reactors

C.5.5.1 General

IEEE Std. 824-2004 should be consulted, but in general design tests on discharge current-limiting reactors shall be made in accordance with the information found in the following subclauses. Design tests on similar units may be used as evidence of compliance provided, as applicable, mechanical stresses, electrical stresses, or maximum temperatures of previously tested reactors, of similar construction, can be shown to be equal to or more severe than those that will be experienced by the newly specified unit.

C.5.5.2 Discharge current test

The discharge current-limiting reactor shall be subjected to a test current not less than 1.1 times the "rated discharge current" as defined in C.4.3. The discharge current test may be carried out with a test current comprising a half-cycle current wave of power frequency, and with the same amplitude. The test shall be repeated 25 times, without evidence of mechanical or electrical damage.

NOTE—The 1.1 factor is applied to the "rated discharge current" to provide and demonstrate margin for service duty.

C.5.5.3 Fault current test

The discharge current-limiting reactor shall be tested to demonstrate that it will carry its rated power-frequency fault current (including peak asymmetrical) for its rated duration without evidence of excessive temperature, or mechanical or electrical damage. The test shall be carried out at power frequency in accordance with 11.6.2, 11.6.3, and 11.6.4 of this standard.

C.5.5.4 Modified short-circuit (mechanical short-circuit/discharge current and thermal short-circuit test) test

As an alternative to the test program described in C.5.5.2 and C.5.5.3, a "modified short-circuit test" as described in this subclause can be performed based on agreement between the purchaser and the manufacturer. This test procedure has evolved within the industry and has been used on various projects. It is suggested that a power-frequency short-circuit test be performed with 10 cycles of symmetrical test current of peak value equal to 1.1 times the peak value of "rated discharge current." A test-current duration of 10 cycles subjects the reactor to 20 peaks of mechanical loading. Since mechanical loading is sustained, this "modified short-circuit test" subjects the reactor simultaneously to mechanical loads of duration and magnitude in excess of any seen in service and is thus a representative demonstration of reactor mechanical integrity. The test is carried out generally in accordance with 11.6.2, 11.6.3, and 11.6.4 of this standard.

The thermal short-circuit test will be identical to that of a standard current-limiting reactor and will be performed at the rated symmetrical short-circuit level for the duration specified. (If not specified, the duration shall be 3 s.)

> NOTE—Test laboratory capabilities: Due to the possibly very high "discharge current rating" of discharge current-limiting reactors, test laboratories may not be able to carry out the discharge current, fault current, and modified short-circuit tests at specified levels. In this case, consideration should be given to verifying reactor capability by calculation.

C.5.5.5 Temperature rise test

The test shall be made according to 11.5 of this standard, mounting the discharge current-limiting reactor similarly to that used in service. Apply rated continuous power-frequency current and measure temperature conditions for the length of time required to reach stable thermal conditions and to establish temperature rise above 40 °C ambient. The temperature rise should not exceed the manufacturer's established limit for the materials used.

C.5.6 Notes for other tests for discharge current-limiting reactors

C.5.6.1 Mechanical resonance test

Due to the repetitive nature of the discharge duty, consideration should be given to performing a test to verify that the winding mechanical resonances are at least 10% away from a value of twice the discharge current frequency, considering the frequency band of the discharge current. The manufacturer shall propose a suitable test procedure. As an alternative, the winding mechanical resonance may be verified by calculation.

C.6 Tolerances

C.6.1 Inductance

The tolerance shall be +10/-0% of rated inductance or as specified. The selection of the manufacturing tolerance for the reactor inductance should take into account possible system interactive effects caused by the reactor/capacitor combination.

C.6.2 Q-Factor

Unless otherwise specified, the "as manufactured" tolerance on Q-factor should be ±20% of the value estimated by the manufacturer.

Unless otherwise specified, the Q- factor, at the discharge frequency and reference temperature, measured at the end of the test sequence, shall not deviate from the value measured prior to dielectric testing by more than 3%.

C.7 Nameplate information

C.7.1 Recommended information

The following information should be included on the nameplate:

a) Apparatus type
b) Manufacturer's name
c) Serial number
d) Year of manufacture
e) Thermal class of insulation
f) Temperature rise, °C
g) Type of cooling
h) Rated power frequency
i) Rated inductance (at rated power frequency)
1) Measured inductance
k) Rated continuous current
1) Thermal current _____ kA _____
m) Mechanical peak current _______ kA
n) Voltage drop
o) BIL
p) Altitude
q) Number and year of specification
r) Number of this standard
s) Total weight

C.7.2 Optional information

Optional information that may be required as follows:

a) Discharge frequency
b) Q-Factor (at discharge frequency)
c) Number of phases
d) Drawing number
e) Customer ID number
0 Service; indoor, outdoor
g) Maximum ambient temperature
h) System voltage

Annex D

(normative)

Reactors Supplied in Enclosures

D.1 INTRODUCTION

Reactors (typically current limiting and motor starting reactors and occasionally filter reactors) may be supplied in enclosures designed by the manufacturer; steel, aluminum or fibre reinforced plastic, FRP, (typically fiberglass polyester resin composite). The enclosure is typically required for personnel protection; especially if the reactor is to be installed in an indoor area with high continuous personnel traffic.

> NOTE—The focus of this section of IEEE C57.16 is on the electro-mechanical design aspects of enclosures supplied with dry-type air core reactors and the impact on the test code when a reactor(s) is supplied in an enclosure. Personnel safety aspects are beyond the scope of this standard and are covered in other documents.

D.2 SPECIAL DESIGN CONSIDERATIONS FOR REACTOR ENCLOSURES

The enclosure shall be designed with sufficient ventilation to ensure that the operating temperature of reactors mounted inside the enclosure do not exceed the temperature rise limits set in this standard. It is crucial that metallic enclosures are designed in such a way that excessive induced losses and associated heating effects do not occur; isolated panels, frame free of shorted loops, etc. If in special cases a special enclosure is provided to reduce the magnetic field, the enclosure may be designed to include closed loops by intention. In this case, it is crucial that such metallic enclosures are designed in such a way that excessive induced losses and associated heating effects are controlled and/or minimized. Entry/exit points for electrical connections shall be designed to avoid flashovers to the enclosure under steady state and transient voltages.

D.3 TESTING

Test code for the reactor shall be interpreted based on the supply of a reactor(s) in an enclosure.

Consideration should be given to performing the temperature rise type test with the fully assembled reactor(s) in the enclosure.

In the case of dielectric tests, such as the lightning impulse test or turn to turn test, the determination as to whether the dielectric test should be carried out on the reactor(s) in the enclosure should be based on the system connection methodology; potheads, bushings, flashover distance from bus or cable, at entry/exit, to the enclosure. If the dielectric test is carried out on the reactor in the enclosure it should be on a type test basis only. Dielectric tests on other reactor/enclosure combinations of an identical order need only be carried out on the reactor.

For an FRP enclosure, induced losses are virtually zero. In the case of a metallic enclosure losses are usually a small percentage of total losses for a well designed enclosure. Measurement of losses with the supplied reactor in a fully assembled enclosure can be expensive due to the assembly time in the laboratory. However if other tests (impulse, temperature rise) are carried out with the reactor in the enclosure then losses can be measured at that time. A “tare factor” can be employed for other reactor/enclosure combinations of an order.

Routine resistance and impedance testing need not be performed with the reactors in the enclosure as the impact of the enclosure on these measurements is usually negligible and that the purpose of the routine test is a manufacturing quality check.

Where short circuit type testing is specified, it should be performed on the reactor in the assembled metallic enclosure. The high magnetic fields generated by the reactor during the test may create significant forces on the enclosure panels. For non-metallic enclosures, it may not be necessary to perform the short circuit test in the assembled enclosure as electromagnetic induced forces do not exist.

Where sound level testing is specified, the sound levels should be measured with reactors assembled in the enclosures. The measurements should be taken along a contour one meter beyond the outside edges of the enclosure.

Annex E

(informative)

Construction and installation of dry-type air-core series reactors

E.1 General description

All parts of dry-type air-core series reactors are "live", unlike oil-immersed reactors and transformers where the tank is grounded. The only external "live" parts of an oil-immersed reactor or transformer are the bushings.

Dry-Type air-core series reactors do not have an iron core. Therefore, the magnetic field is not constrained and will occupy the space around the dry-type air-core reactor. Although the magnetic field strength is reduced with increase in distance from the reactor, the presence of this field should be taken into consideration for the installation of dry-type air-core units. The extent to which care has to be taken is largely a function of kilovoltamperes and is lower for low kilovoltampere units.

In the following subclauses, application-related construction details and installation considerations will be discussed in order to provide guidance to the user of dry-type air-core series reactors.

E.2 Safety

Since dry-type air-core series reactors are not enclosed in a grounded tank, parts above the base support insulators should be treated as "live." Therefore, in order to meet personnel safety requirements, the reactor shall be installed with clearances established by the National Electric Safety Code® (NESC®) (ASC C2, applicable edition). For transmission voltage class and distribution voltage class equipment, standard methods of achieving personnel clearance are the use of fencing and special support structures. In many cases, both methods are employed simultaneously. Distribution voltage class series reactors are also installed in cells fabricated from standard building materials or vendor supplied enclosures.

When fencing is employed, special care should be taken to ensure that the stray magnetic field of the series reactor does not induce high currents in metallic fencing components. All metallic fencing should be broken up into electrically isolated sections if it is located very near the reactor. It is also critical to ensure that all portions of a metallic fence are grounded because of the capacitive coupling that can exist between the reactor, which is at high potential, and the fence. Another alternative is to use nonmetallic fencing, e.g., wood or plastic.

If distribution class series reactors are mounted in cells fabricated from standard building materials, the use of rebar should be fully analyzed, preferably by the reactor supplier, to determine eddy current heating based temperature rise. Metallic structural members are also a concern. Standalone enclosures of steel or fiberglass are also employed for personnel protection. Care should be taken to sectionalize enclosure panels to avoid induced current heating and possible excessive mechanical loads during short-circuit duty. Grounding of panels should also be done in such a way as to avoid creation of closed loops. Reactor manufacturers can often provide specially designed enclosures to minimize enclosure size and ensure proper grounding, panel size, and isolation. Designs very often require sophisticated computer analyses backed by empirical data from in-service experience and short-circuit testing.

Special mounting structures can also be employed to provide safety clearance for substation personnel. Methods employed include fiberglass pedestals, braced aluminum and steel pedestals, special grounded metallic support pedestals, and reinforced concrete structures. The type of material (aluminum, mild steel, austenitic stainless steel) that can be employed is a function of magnetic field strength, field direction, structure geometry, and mechanical considerations. In the case of concrete structures, eddy current heating in rebar should be fully assessed and may necessitate the use of nonmetallic (fiberglass) or austenitic stainless steel reinforcing rods.

When employing dry-type air-core series reactors, care should be taken in the installation of the station ground grid in the vicinity of the reactors. The ground grid should be designed to limit currents induced in it to an acceptable value. Grounding of other ancillary support structures or equipment in the vicinity of the reactors should be accomplished without creating closed loops in the grounding system.

As a prudent safety precaution all grounding of reactor ancillary components, enclosure panels and frame, metallic fencing, ground grids, etc., should be inspected and tested on a regular schedule.

E.3 Site conditions

Site conditions should be taken into consideration in the application of dry-type air-core series reactors. It is preferable if unusual site conditions are made a part of the specification so that the reactor can be designed accordingly.

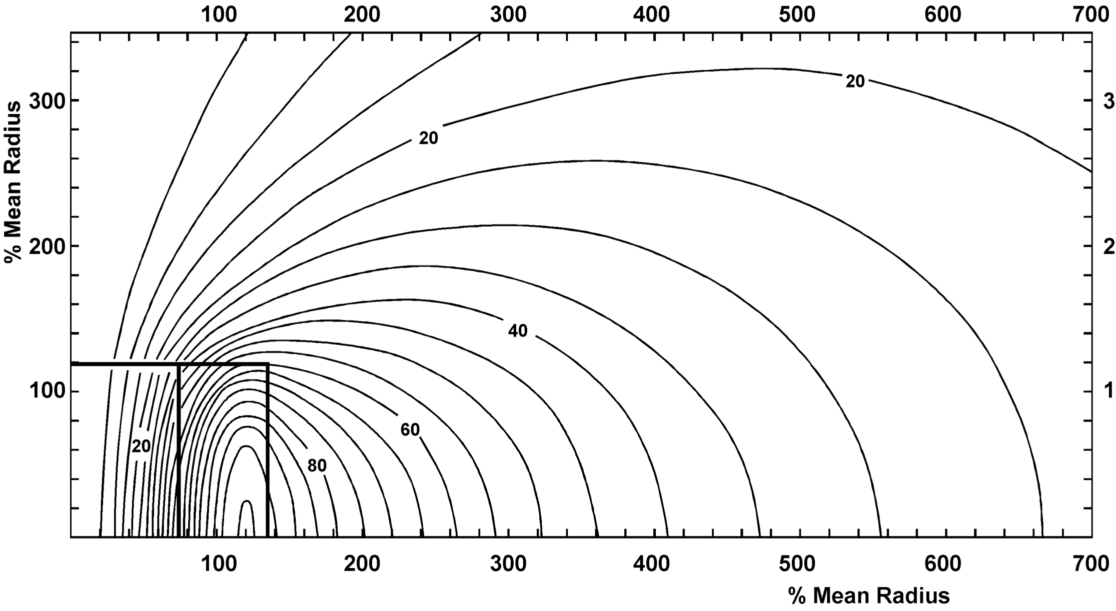
Pollution is an important factor. Many reactors are installed in industrial applications in utility applications or near to sources of industrial pollutants. Coastal installations are also critical; even for installation some distance inland. Salt pollution effects are a function of storm severity, direction of winds, and severity vs. frequency considerations. Mitigation techniques can include, in the case of the reactor, lower surface voltage stress, special track-resistant coatings such as room temperature vulcanizing silicone rubber (RTV) acid or caustic resistant paints, etc. Mounting insulators and bus support insulators may have to be high-creepage designs, may utilize RTV coating protection, or may require other techniques.

Ambient temperature at the point of installation is an important factor. Most specifications quote maximum ambient temperatures based on weather office data. However, more critical is temperature at the site, specifically the area of installation. The issue is not only solar radiation effects but also the temperature of the cooling air, which could be significantly higher than the air temperature in the shade. Nearby buildings, or walls erected around reactor installations, all can have an effect on the cooling air temperature and the air flow seen by the reactor. Although difficult to quantify, even a descriptive clarification in the reactor specification would be a very useful design aid.

E.4 Clearances: Electrical, ventilation, and magnetic

The clearance requirements are of three types: electrical, ventilation, and magnetic.

As the normal dry-type air-core series reactor has exposed live parts at essentially all points on its outer surface, provision must be made for electrical clearance from the reactor surface to nearby grounded surfaces and to the surface of other reactors in adjacent phases. Standard electrical clearances to live parts are perfectly adequate. No special precautions over and above normal substation practices are required. Ventilation clearance requirements may vary somewhat depending on the reactor manufacturer. For instance, in the case of reactors employing vertical cooling ducts, provision should be made for the unimpeded entrance and exit of cooling air at the bottom and top of the cooling ducts, respectively. Generally, the ventilation clearance will be less than the magnetic clearance requirements and, as such, it will not prove to be a limiting factor when installing the unit. Irrespective of this fact, it is still important to recognize that there is a requirement for ventilation and the blockage of the cooling ducts with any foreign material, metallic or non-metallic, or interference with normal convective air flow should be avoided. Magnetic clearance requirements arise since dry-type air-core reactors have no iron core to capture the magnetic field. See Figure E.1.



NOTES

1—Reactor center located at origin.

2—Flux lines marked in percent of maximum flux.

3—Horizontal and vertical axes are in percent of the mean radius of the reactor.

Figure E.1—Single quadrant plot of flux surrounding a typical reactor

These stray magnetic fields can induce currents in structural metallic parts that may give rise to serious heating under normal load conditions and to severe forces under short-circuit conditions. The induced currents are of two types, and, as such, they give rise to two types of clearance requirements.

a) Eddy currents caused by the local field give rise to a minimum clearance required to metallic parts that do not form closed loops.
b) Circulating current caused by coil flux linking a closed loop formed by a number of structural members lead to a minimum distance that shall be maintained between the reactor and parts that form closed electrical loops.

A very common, albeit understandable, misconception, is the belief that these "magnetic clearances" apply to magnetic materials only, and not to other metallic but nonmagnetic parts. This is not true. While it is true that nonmagnetic materials such as aluminum may often be used in place of steel to reduce the severity of heating problems caused by stray reactor fields, it should be recognized that structural parts constructed of these materials will also carry sizable currents, experience heating due to the presence of the coil field, and perhaps have substantial forces impressed on them when the reactor carries short-circuit current. The only difference is that for some conditions the heating will be less severe when nonmagnetic, low-resistance materials are used.

The effect of the stray magnetic field shall be considered in the support structure design, as well as in the placement of auxiliary equipment such as circuit breakers, lightning arresters, etc. Additionally, any other required nearby structures shall be located in areas where the effect of the stray magnetic field will not create excessive heating. Figure E.2 illustrates conservative "rules of thumb" that will keep the end user out of trouble.

As can be seen from Figure E.2, the clearance required to closed loops is approximately double that required for parts that do not form closed loops. For this reason, it is best, particularly in the case of new installations, to design the structural parts near the reactor in such a way as to avoid the formation of closed loops. For existing installations that are being modernized or upgraded, however, the generally troublesome structural parts, such as concrete reinforcing rods and building support beams, are already in place and as such it may not be possible to avoid the presence of closed loops. In this case, the required reactors may still be fit into the desired space even if the general magnetic clearance requirements shown in Figure E.2 are not satisfied. This may often be accomplished simply by performing a detailed magnetic clearance analysis to confirm that the guidelines may be reduced for the specific case in question. In more difficult cases, the use of appropriate materials, geometries, and shielding may provide the necessary reduction in clearance requirements.

If insulators and associated support structure are supplied with the reactor, it is desirable that they be of sufficient height to provide the required magnetic clearance to the foundation on which the reactor is to be mounted. Sufficient information regarding metallic parts below the reactor (rebar, structures, ground grids) shall be provided by the purchaser to the manufacturer.

E.5 Mechanical considerations

Depending on the scope of supply, special attention should be given, by either the manufacturer or purchaser, to the interactive electromagnetic forces between stacked reactors, between reactors installed close to each other, between the reactor and current-carrying auxiliary parts (such as buswork), and between the reactor and bus or cable connections to the reactor. Support structure and bracing elements shall be designed to resist the resultant loads.

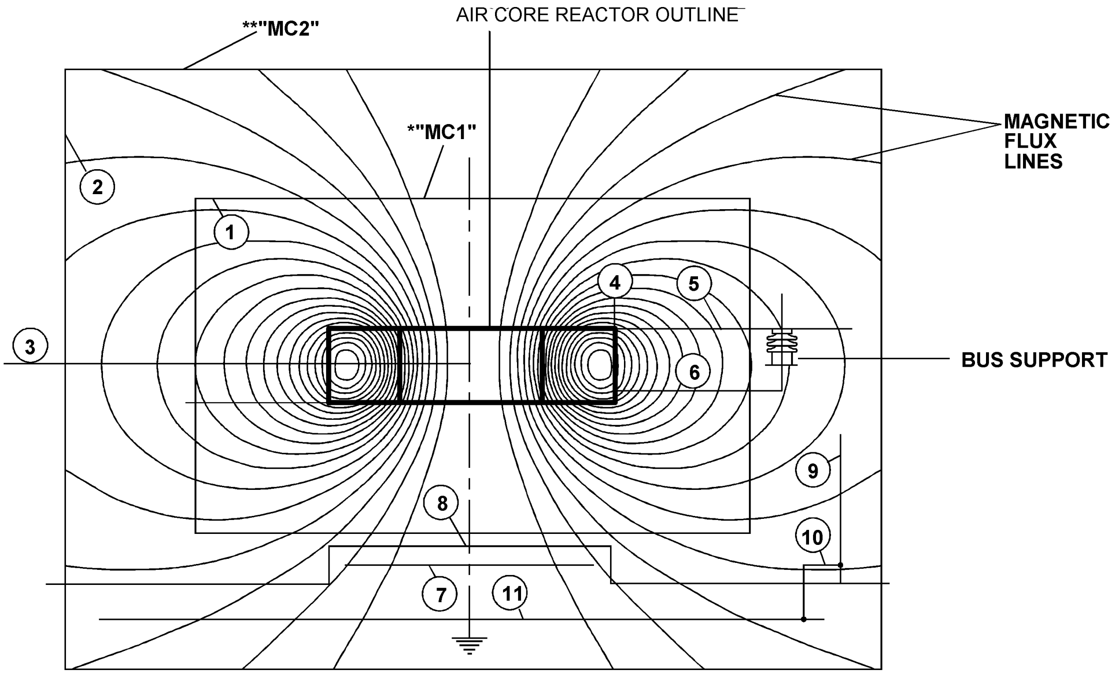
As standard practice, unless otherwise specified, peak wind loads and electromagnetic forces created by a simultaneous three-phase fault (again, unless otherwise specified) are assumed to occur simultaneously. Seismic loads or other specified loading are typically assumed to act on a non-coincidental basis.

Reactors should be designed to facilitate lifting and should be provided with lifting eyes or similar devices to allow safe, rapid installation. Lifting and handling instructions should be clear and readily available. In the case of very heavy reactors, special crating and transport precautions may have to be taken to keep stresses in the reactor at safe levels. Likewise, special lifting devices and procedures may have to be employed.

E.6 Concrete foundation and mounting

Foundation and mounting requirements are a function of the rating and hence mass of the reactor. Many low kilovoltampere units (<1 MVA) are mounted indoors with no special precautions other than magnetic clearance considerations. Larger units mounted indoors may require the use of vibration isolators. For large units mounted outdoors, one basic rule of thumb that should be considered, as with the mounting of any large piece of equipment, is to keep the foundation at least two or three times the mass of the object mounted on it. This will ensure there are absolutely no ground vibration based noise problems in the field. If bedrock at the site is very near the surface or soil conditions warrant, a less massive foundation can be used.

Generally for dry-type air-core series reactors, the other critical foundation or floor design criterion is to ensure that the stray magnetic field of the reactor does not create excessive heating in the reinforcing material. In most cases, for outdoor mounted units the distribution of the coil mass on the concrete base results in the concrete being very lightly loaded. Therefore, rebar may not be necessary. If rebar is necessary, non-metallic or stainless steel rebar would eliminate potential eddy heating problems. Also, where metallic rebar is used, the crossover points should be electrically isolated to prevent closed loops. Pieces of hose slipped over the rebar at the crossover would be sufficient. If clearances greater than the coil diameter are used below the reactor, then precautions of isolating the rebar to prevent shorted loops and selecting stainless steel or non-metallic materials may not be necessary.



1) Keep small metallic parts not forming closed loops outside "MC1"*.
2) Keep large metallic geometries or closed loops outside "MC2"+.
3) Keep spacing requirements to neighboring reactors to avoid:
    a) Unacceptable mutual influence on inductance:
    b) Inadmissible electrodynamic forces acting between adjacent reactors during maximum short-time current.
4) Use adequate connectors having geometries not providing too large a frontal area to the magnetic field in order to minimize eddy heating.
5) Select adequate connection bars or cable with respect to eddy heating and align them in radial direction from the reactor terminal.
6) Provide connection bus bar or cable/bus supports close to the reactor to relieve the reactor terminals of undue mechanical loads.
7) Insulate crossover points of rebar.
8) Provide even and level foundation plane.
9) Partition metallic fencing erected in the reactor vicinity into electrically insulated sections that are individually grounded.
10) Do not form shorted loops when grounding the fence sections.
11) Avoid shorted loops in the station ground grid.

*"MC1" Magnetic clearance contour: 1/2 coil outer diameter from all surfaces of the reactor.

+"MC2" Magnetic clearance contour: 1 coil outer diameter from all surfaces of the reactor.

Figure E.2—Installation guidance—Summary (basic rules)

The final major consideration is the anchoring system used to secure the coil support structure to the concrete base. The anchors shall be located deep enough in the concrete and be designed to resist the overturning load imposed on the coil and its structure due to wind loading, short-circuit forces or seismic excitation. This is most important for reactors located on top of tall support structures (e.g., fiberglass pedestals) to give required clearance for station personnel. Again, the manufacturer of dry-type air-core series reactors is the best source of definitive information.

One unique aspect of high-voltage reactors is that the structure required underneath the reactor both for voltage and personnel clearance usually results in low levels of magnetic field at the foundation, and thus the foundation may typically be built using standard methods. However, to ensure there are no problems, the manufacturer of the reactor should conduct a detailed analysis.

E.7 Connections

In the case of low kilovoltampere rated units, the only consideration regarding connections is that of ampacity and desired terminal temperature rise. However, because of the very intense magnetic fields that exist close to large megavoltamperes dry-type air-core reactors, special care should be taken in designing terminals, connectors and connections to the system. Terminals should be streamlined to the magnetic field in order to minimize eddy current heating. Connectors employed should also follow the same criteria. Since eddy losses are proportional to the geometry to the fourth power, it is preferable to use stranded cable instead of solid bus bar for making system connections to the reactors. However, solid bus bar can be used provided increased ampacity is employed to compensate for the eddy heating. It is also of benefit if the bus bar is rectangular and is oriented in such a direction that the coil's magnetic field impinges at the direction of its narrowest section. It should be stressed, however, that short-circuit forces on connections should be iterated into the selection process and include such considerations as additional support points, flexible links, etc.

E.8 Auxiliary protection

Modern, dry-type air-core reactors can be designed to meet any system BIL requirement. It should be pointed out that BIL requirements normally are based on switching or standard lightning impulse conditions. In modern power systems, it is possible that reactors can be subjected to very fast rising transient overvoltages. If these are known about in advance, they can be considered in the design of the reactor. However, in many cases, it is hard to predict the rate of rise or the magnitude of such transients and, in these cases, auxiliary protection such as the use of surge arresters may be advisable. Any such decision should be based on in-depth discussions with the reactor manufacturer and detailed systems analysis.

E.9 Switching: Circuit breakers

Circuit breakers are normally utilized to switch the circuits of which series reactors are a component. The two things that should be considered are the effect of the switching operation on the insulation system of the dry-type air-core series reactor, and the transient recovery voltage (TRV) applied to the circuit breaker. Detailed high-frequency coupled circuit models developed for dry-type air-core series reactors allow proper analysis of most situations. Therefore, the insulation system of the reactor can be designed appropriately, the proper breaker selected, or the high-frequency characteristic of the reactor may be modified to reduce breaker TRV.

E.10 Indoor Installation

When reactors are installed indoors vs. outdoors additional criteria should be taken into consideration. It is especially critical to utilize the input/expertise of the reactor manufacturer. These include:

1. The presence of “rebar” in floors, walls and ceiling should be determined and assessed. If induced heating effects produce excessive temperature in the “rebar”, shielding may be required. Civil engineering expertise should be sought to determine safe temperatures for “rebar” in concrete.

2. Ventilation should be adequate and is a function of the losses of the reactor installation. The reactor manufacturer can supply information on cooling and “make-up” air requirements; for instance m^3/min. inlet air flow. It is very important to ensure that forced ventilation does not negatively impact the cooling of the reactor; impede natural convection air flow in the reactor cooling ducts.

3. The effect of the reactor(s) magnetic field on instrumentation etc. in adjacent areas should be assessed and shielding applied if required.

4. Careful attention should be paid to any electrical closed loops around the reactors. Guidance on manufacturer's drawings generally provides clearances with respect to heating effects caused by induced currents. However these clearances do not take into consideration any ancillary effects of induced EMF or higher resistance "contact points" in a closed loop circuit. Magnetic field analysis for a specific installation and equipment rating may be available from the equipment supplier upon request.

5. Building access and handling equipment should be evaluated and taken into consideration.

6. Dielectric clearance and "flashover distances" should be reviewed.

7. Reactors of higher MVA rating or those with high harmonic current loading, such as some filter reactors, may require more care and consideration for indoor installation.

8. In addition to potential induced current heating effects care should be taken on electrical conduits or water pipes and possible "emf" induced arcing across open or poor electrical connection points.

E.11 Supporting Documentation

[E1] Payne, Paulette, "Design and Installation of 13.8kV Current Limiting Reactors for the PEPCO System, Electrical Equipment Committee, Pennsylvania Electric Association, Hershey, Pennsylvania, Sept. 10, 1991.

[E2] Caverly, David S. and Patel, Ramesh H., "Air Core Reactors: Important Considerations for Their Specification and Application", Canadian Pulp and Paper Association Meeting, Montreal, PQ, Canada, Feb. 1984.

[E3] Harlow, James H. (Editor) "Electric Power Transformer Engineering (Second Edition), CRC Press, 2007, Chapter 10-1 Reactors.

Annex F

(informative)

TRV Considerations in the Application of Current-Limiting Reactors

F.1 Background

The specific focus of this annex is to alert utilities and large industrial “end users” to the possible circuit breaker TRV issues associated with the application of current-limiting reactors under fault conditions; mitigation solutions to TRV problems caused by the use of current limiting reactors are also given. One of the most common forms of mitigation is to utilize capacitors. The capacitors are typically within the scope of supply of the reactor manufacturer. This fact was the prime motivator for including this annex in IEEE C57.16. Capacitors are very often mounted inside distribution class current limiting reactors, but in the case of HV series reactors, the required HV capacitors are separately mounted. The information presented in this annex is not intended to duplicate detailed technical efforts of the IEEE Switchgear Committee; it is only intended to complement such work in relation with the application of current-limiting reactors. Many relevant references on circuit breaker TRV produced by the IEEE Switchgear Committee are included in “F.10 Supporting Documentation”. It should be emphasized that valuable input was received from members of the IEEE Switchgear Committee during the drafting of this annex.

F.2 Introduction

When a circuit-breaker (CB) interrupts current, under either fault or steady state conditions, a voltage appears across the terminals (contacts); starting from a value corresponding to the arc voltage and rising, in a transient timeframe until the steady state bus voltage on the source side and the steady state voltage on the line side (zero if de-energized) are reached. Hence, it’s designation as TRANSIENT RECOVERY VOLTAGE (TRV). Since TRV typically becomes significant under fault conditions, the material in this annex is confined to the application of current-limiting reactors and the resulting possible circuit-breaker TRV issues. The circuit-breaker should not only interrupt the fault current, but it also should withstand the recovery voltage and its associated transient recovery voltage (rate of rise) without restrike across its contacts. Circuit-breakers are, therefore, rated on their ability to interrupt fault currents of specified magnitude with defined TRV parameters.

F.3 Transient Recovery Voltage Capability of Circuit-Breakers

There are three parameters that define the severity of a transient recovery voltage with respect to the capability of the circuit breaker; the rate of rise-of-voltage, the peak of the voltage and the time delay. (See ANSI/IEEE C37.011-2005 for a complete definition.) These parameters are functions of circuit elements, as well as type and magnitude of the fault.

IEC SC17A/WG35 developed new sets of TRV values for circuit-breakers rated 72.5 kV and below (see [F11] and [F12]); including the application criteria for circuit-breakers used on overhead line systems or cable systems). The IEEE Switchgear Committee is evaluating the possibility of using the same set of TRV values as defined by the IEC Working Group. The IEC values for cable systems are the old TRV values used in IEC 62271-100 or IEC 60056 while the values for overhead line systems were taken from the IEEE Standards for outdoor circuit-breaker applications. In the present revision of ANSI/IEEE C37.011 (see [F1]) IEEE has adopted the IEC cable system values for indoor applications. TRV values for cable and line systems are also included in ANSI/IEEE C37.011-2005. Note at the time of completion of this revision of IEEE C57.16, a revision process for IEEE C57.011 was in process; Section 4.4.2 will contain information re TRV and reactor limited faults.

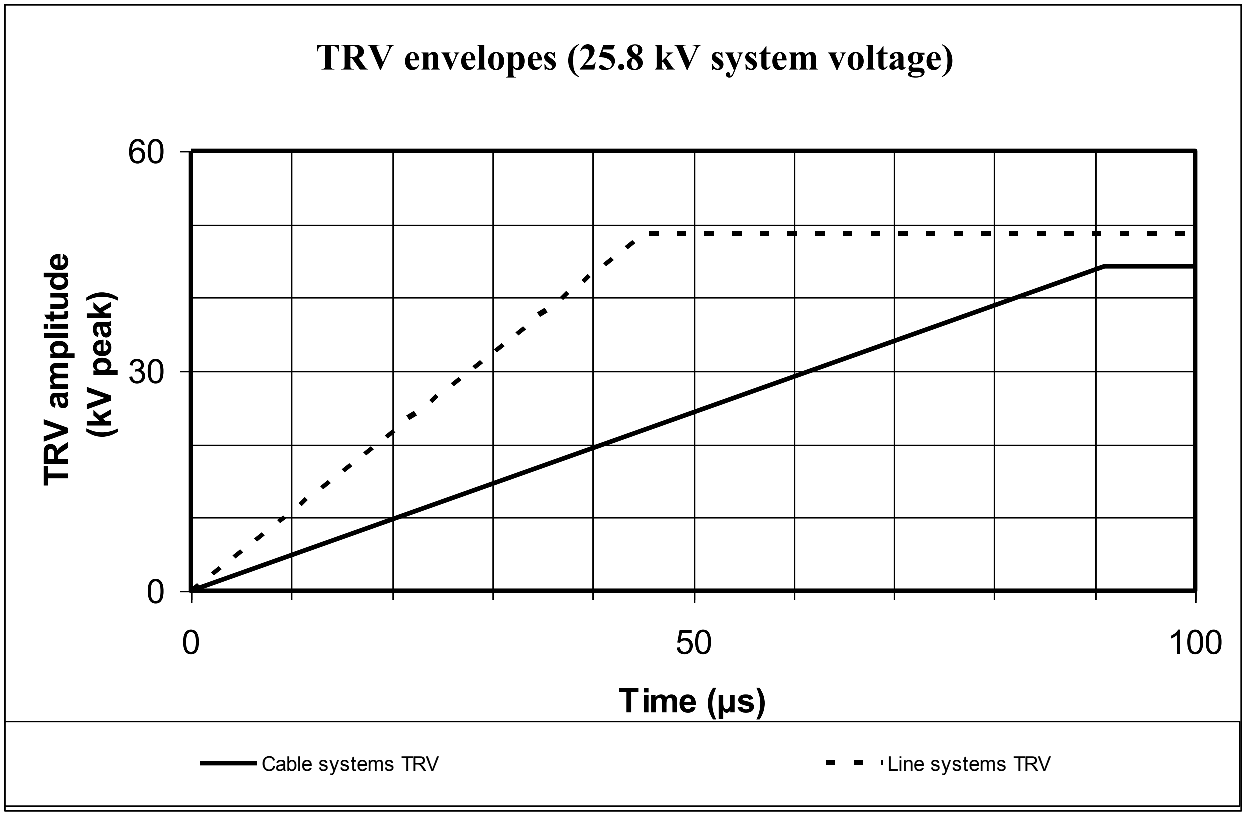


Figure F.1 Examples of TRV envelopes for two different system applications (overhead line and cable system) for circuit-breakers of the same system voltage rating (25.8 kV).

NOTE—TRV "envelope" can be defined in terms of rate-of-rise, time to peak voltage and peak voltage.

F.4 System Parameters That Impact Circuit-Breaker TRV When Used With Current-Limiting Reactors.

System parameters that impact circuit-breaker TRV are as follows.

1. System neutral connection e.g. effectively grounded or non-effectively grounded.
2. Circuit inductance e.g. ratio of the current-limiting reactor reactance versus the total circuit reactance.
3. Capacitance to ground:

    a) Interconnection methodology between transformers, current-limiting reactors and circuit-breakers can impact the TRV seen by a circuit-breaker. A cable connection instead of an air-insulated bus bar connection may mitigate a circuit-breaker's TRV problem (higher capacitance to ground). The use of cable is most likely in distribution networks/substations.

    b) In transmission systems, the presence of capacitive voltage transformers (CVTs) and coupling capacitors (PLC systems) may also attenuate a circuit-breaker's TRV.

F.5 Type of Fault

Power transformer reactance plus system reactance and transformer stray capacitances may alone result in TRV exceeding the circuit-breaker ratings. The application of reactors will further acerbate the problem because of the inherent low stray capacitance which results in a high natural resonant frequency for dry-type air-core current limiting reactors.

Many utilities have applied series current limiting reactors with no consequential TRV issues on their circuit-breakers. On the contrary, other utilities have also experienced circuit-breaker failures, some catastrophic, after having added series current-limiting reactors or by having replaced a circuit-breaker by another circuit-breaker using a different arc extinguishing technology on an existing circuit that incorporates a current-limiting reactor.

F.6 Series Reactor Application and Circuit-Breaker TRV Considerations

Since transient recovery voltage characteristics are a function of system configuration, introducing an inductance into a system does impact transient recovery voltage characteristics across the circuit-breaker during a fault condition. The introduction of a current-limiting reactor (CLR) or any significant lumped reactance such as a power transformer tends to increase the rate-of-rise of transient recovery voltage (RRRV), which might exceed the rated value defined for a particular circuit-breaker (see [F1], [F9], [F11], [F13] and [F14]). Moreover, some circuit-breaker technologies are more sensitive to the RRRV than other technologies. Systems configuration (layout)/parameters together with circuit-breaker capabilities and/or technology are the key factors impacting TRV and the behavior of such combinations should be carefully studied using a network transient simulation program.

F.7 TRV Origins

In order to understand the origins of circuit-breaker TRV and the impact a current-limiting reactor has on it, it is first convenient to recall that transients in power systems are the consequence of a redistribution of energy among the system components, in a very short, but finite, time following any change in the circuit configuration. Also the redistribution of energy obeys the principles of energy conservation, i.e. the rate of supply of energy (source) is equal to the rate of storage of energy (in capacitors and reactors) plus the rate of energy dissipation (in resistors). It is also important to keep in mind that in transient phenomena, not only physical elements, such as reactors and capacitors, are relevant, but also stray capacitances of components in the immediate vicinity of the object under consideration must be taken into account.

F.8 Examples

The example distribution feeder substation circuit shown in Figure F.2 will be used to illustrate the transient recovery voltage in a simple system typical of North American practice. A current-limiting reactor may be installed either before or after the circuit breaker. An equivalent single-phase circuit simulating the first-pole-to-clear of a circuit-breaker during a three-phase fault in a non-effectively grounded system (first-pole-to-clear factor of 1.5) has been used and it is shown in figure F3. The three-phase fault is assumed to be directly applied at the feeder side of the circuit-breaker terminals.

The method of calculation used in the example is a voltage source EMTP study. Other calculation methods are also used such as the current injection method used in various IEEE circuit breaker application guides: refer to IEEE Std. C37.011-2005 and IEEE Std. 328-1971 (ANSI C37.0721-1971).

The main advantage of using a current-limiting reactor is to reduce the fault current magnitude on the feeder side. Very often, distribution networks are designed for a relatively low value of short-circuit current in order to cope with the capabilities of protective and / or switching devices such as expulsion fuses, disconnectors and load switches, the tank rupture withstand levels of distribution transformers, or the interaction of fault currents with parallel communication circuits. Moreover, by using a current limiting reactor located on the source side of the feeder circuit-breaker, the short-circuit current rating of the feeder circuit-breaker can be reduced accordingly and a less expensive circuit-breaker may be used. Current-limiting reactors are also typically installed after the circuit breaker but in this case a lower fault and duty rated circuit breaker cannot be used.

NOTE—Further discussion of the rationale re the location of the CLR vs the CB can be found in the references.

NOTE—In order to provide additional background information, the following discussion re North Amercian vs. European practice in this application of current limiting reactors is included.

In general, European distribution circuits have their neutral isolated or grounded through a high impedance. The neutral is considered to be a "non-effectively earthed neutral". This is due to the fact that European distribution systems are three-phase based (even for residential) instead of the single-phase distribution systems as are used in North America. This may allow a permanent or a long duration phase-to-ground fault without interrupting electricity supply to clients.

Knowing that single-phase faults represent generally more than 90% of the total number of faults, using "non-effectively earthed neutral" distribution systems increases the availability of power supply to the users.

European utilities seldom use current limiting reactors on their distribution feeders. Big parts of their distribution systems (at least in small, medium and large cities) are built with cables instead of overhead distribution lines as are used in North America. Single phase-to-ground faults do exist but do not result in large fault currents as in single-phase systems. Electromagnetic forces during single-phase faults are thus essentially non-existent in "non-effectively earthed neutral systems". Significant fault current in "non-effectively earthed neutral systems" may only occur during double earth faults (phase-to-phase faults) or during three-phase faults. If screened cables are used, then the magnetic forces caused by the fault currents also do not exist. With "belted" cables, forces may be present. In addition, European systems generally use current limiting fuses instead of expulsion fuses as are generally used in North America. Current limiting fuses do limit the peak and the duration of fault current to low values thus limiting forces accordingly. Current limiting fuses may cope with high prospective currents (around 10 kA r.m.s. is a typical value).

Due to the fact that North America utilities use expulsion fuses (much lower cost than current limiting fuses and less sensitive to overloads) allows for an economic mechanical construction of distribution overhead lines (costs of building such lines). North American utilities limit the amplitude of fault currents to values that the expulsion fuses can cope with. This is why current limiting reactors are used on North American distribution feeders.

Another advantage of using current limiting reactors is that it may permit the use of a lower circuit-breaker rating (lower cost circuit-breakers).

Using current-limiting reactors to reduce fault currents also reduces short circuit mechanical stresses in power transformers, bus support systems, customer switchgear, etc.

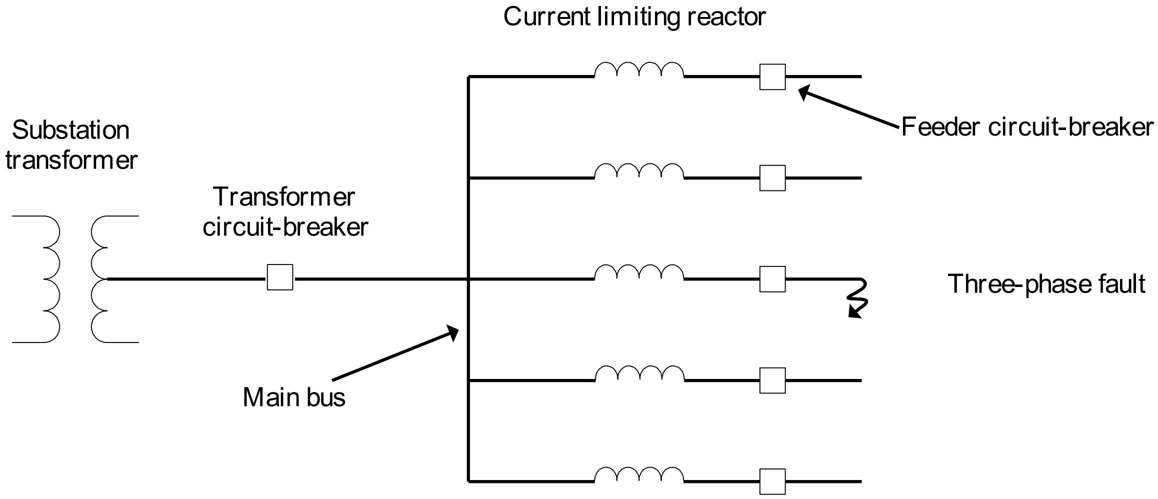


Figure F.2 Typical single-line diagram illustrating the use of current-limiting reactors in distribution feeder substations.

NOTE—As shown in figure F.2, the current limiting reactors are located on the source side of the feeder circuit-breakers. Topologies having the current limiting reactors located on the load side of the circuit-breakers are also used. Although the fault current on the distribution feeder is the same if the reactor is located on the source side, a fault occurring between the feeder circuit-breaker and the current limiting reactor will produce a fault current magnitude equal to the main bus fault current which the circuit-breaker may not be designed to interrupt.

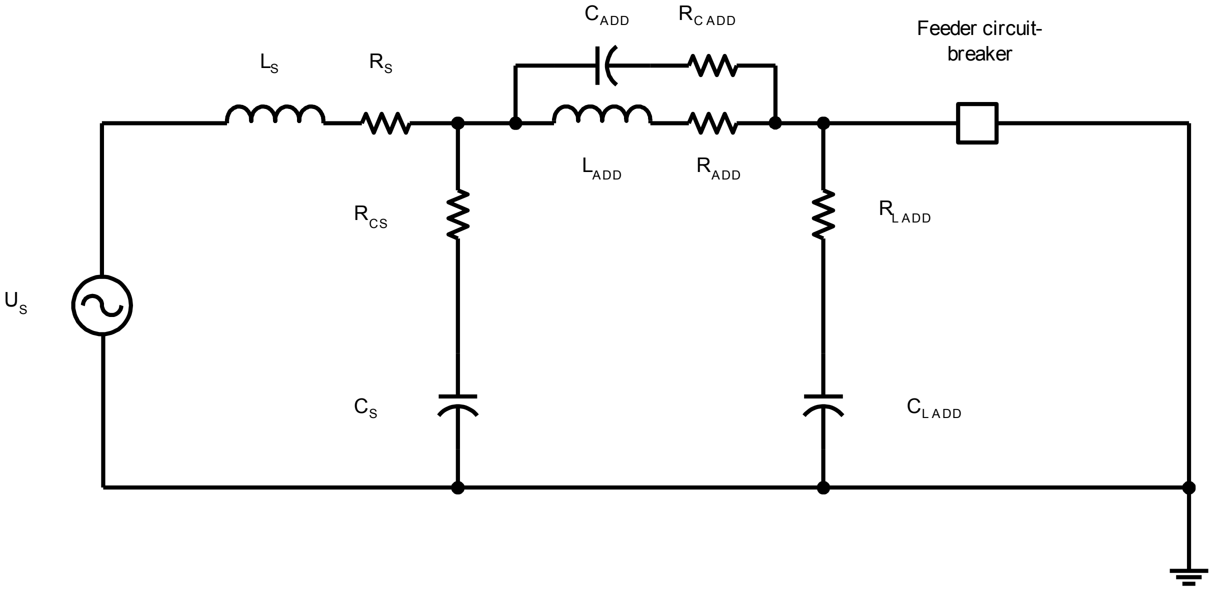


Figure F.3 Equivalent single-phase circuit used in the examples representing the first-pole-to-clear during a three-phase fault.

Circuit elements are defined as follows:

NOTE—For this simulation of the first-pole-to-clear in an non-effectively grounded system, the first pole to clear factor is 1.5.

U_S is the system voltage. The r.m.s. single-phase system voltage is considered to be 1.5 x $U_S / \sqrt{3}$;

L_S is the inductance of the system and the transformer. The single-phase inductance is considered to be 1.5 x L_S;

R_S is the equivalent resistance of the system;

C_S is the equivalent shunt capacitance of the system and transformer including transformer winding, transformer bushing and bus bar. The single-phase equivalent capacitance is considered to be 2/3 x $C_{S;}$

R_{CS} is the equivalent high frequency losses of the system and transformer; including transformer winding, transformer bushing and bus bar. The single-phase equivalent capacitance loss is considered to be 1.5 x R_{CS};

L_{ADD} is the inductance of the current-limiting reactor. The single-phase equivalent inductance is considered to be 1.5 x L_{ADD};

R_{ADD} is the power frequency resistance of the current-limiting reactor. The single-phase equivalent resistance is considered to be 1.5 x R_{ADD};

C_{ADD} is the capacitance between the current-limiting reactor terminals. The single-phase equivalent capacitance is considered to be 2/3 x C_{ADD};

$R_{C\,ADD}$ is the equivalent high frequency loss of the resonant circuit between the current- limiting reactor terminals. The single-phase equivalent capacitance losses is considered to be 1.5 x $R_{C\,ADD}$;

$C_{L\ ADD}$ is the capacitance to ground of the current-limiting reactor. The single-phase equivalent capacitance to ground is considered to be 2/3 x $C_{L\ ADD}$;

$R_{L\ ADD}$ is the equivalent high frequency loss of the resonant circuit to ground of the current-limiting reactor. The single-phase equivalent capacitance losses is considered to be 1.5 x $R_{L\ ADD}$;

Since the circuit frequency response is much higher than power frequency, high frequency resistance values should be used for transient recovery voltage calculations.

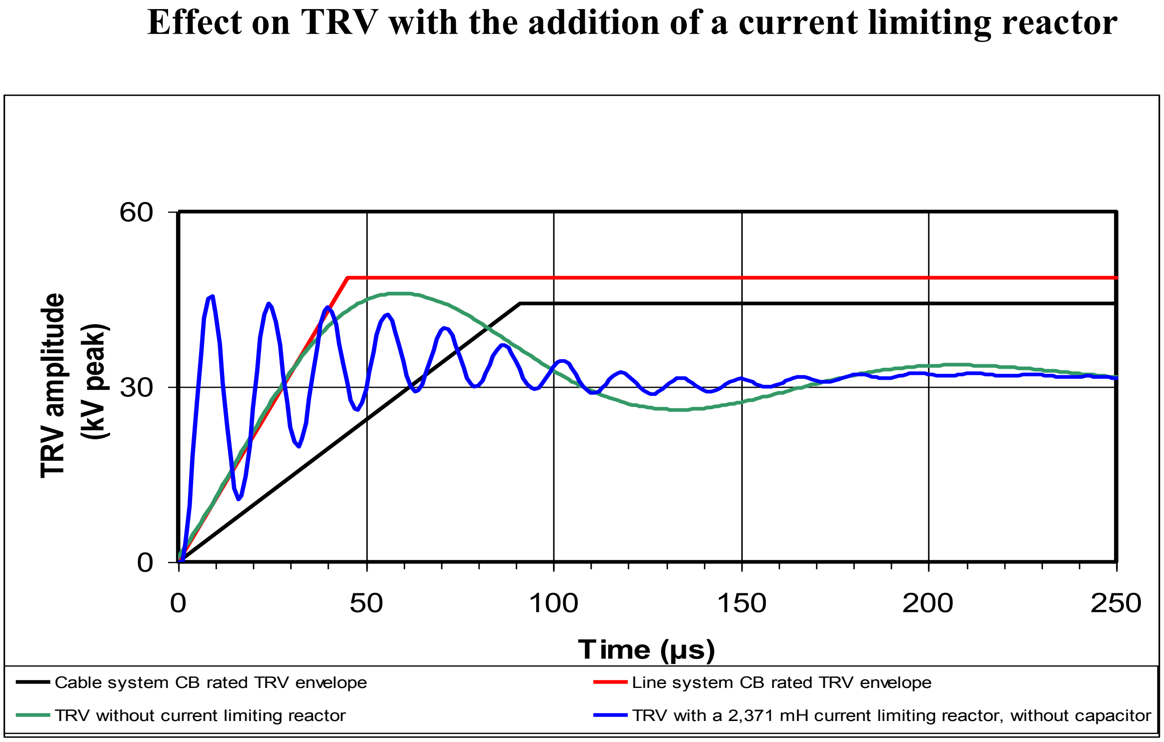


Figure F.4 Example of the effect of adding a current-limiting reactor to the circuit-breaker TRV during fault condition.

Figure F.4 shows the effect on the transient recovery voltage of the circuit-breaker after having added a series current limiting reactor. In this example the following parameters have been considered:

U_S: 22.3 kV r.m.s. (1.5 x 25.8 kV / √3);

L_S: 1,183 mH (1.5 x 0.789 mH). This inductance limits the fault level on the main bus to 50 kA r.m.s. sym.;

R_S: 0,026 Ω (1.5 x 0.017 Ω; X/R = 17);

C_S: 0.403 µF (2/3 x 0.604 µF). This capacitance has been specifically chosen to reach the upper limit of the TRV envelope specified for circuit-breakers intended to be used on overhead line systems;

R_{CS}: 30,7 Ω (1.5 x 20.5 Ω). This resistance value has been specifically chosen in order to be close to the upper limit of the TRV envelope specified for circuit-breakers intended to be used on overhead line systems;

L_{ADD}: 3.557 mH (1.5 x 2.371 mH). This inductance limits the fault level on the main bus to 12.5 kA r.m.s. sym.;

R_{ADD}: 0.0134 Ω (1.5 x 0.0089Ω; X/R = 100);

C_{ADD}: 712 pF (2/3 x 1.068 nF). This capacitance has been specifically used in order to achieve a 100 kHz natural resonance frequency (typical value for 25.8 kV dry-type current-limiting reactors);

$R_{C\ ADD}$: 373 Ω (1.5 x 249Ω) This resistance value corresponds to a tan δ of 0,01%;

$C_{L\ ADD}$: 1.0 nF (2/3 x 1.50 nF);

$R_{L\ ADD}$: 250 Ω (1.5 x 249Ω) This resistance value corresponds to a tan δ of 0.01%.

For the specifics of the above "tailored" example (values of parameters were specifically selected to produce a desired TRV result and may not reflect "real life" situations) the addition of the current-limiting reactor increases the TRV slope from 1.08 kV/µs (maximum rate-of-rise for circuit-breakers intended to be used on overhead line systems) to approximately 6.0 kV/µs which is far above the rated TRV envelope for such a circuit-breaker. This situation may impair the circuit-breaker ability to interrupt and possibly even result in failure of the circuit breaker; the circuit-breaker being unable to cope with this severe TRV rate-of-rise.

In order to reduce the TRV rate-or-rise to an acceptable level, it is necessary to add either a parallel capacitor across the current-limiting reactor or a phase-to-ground capacitance on the feeder side of the current limiting reactor such as that provided by a capacitor, a capacitive voltage transformer or by an HV cable. The additional capacitance should be adequately sized to decrease the rate-of-rise of the resulting TRV below the rated TRV envelope defined for the circuit-breaker utilized (line or cable system rated circuit-breaker). It should be noted that the simple addition of a low loss capacitor may result in a TRV peak value which exceeds the maximum rated peak value defined for the circuit-breaker. In such cases, a resistor connected in series with the additional capacitor may be necessary. It must, however, be emphasized that a high frequency model of the series reactor should be used in TRV studies; including high frequency losses which can be significantly higher than at power frequency. Such high frequency reactor losses are equivalent to adding an additional series resistor to the TRV capacitor element to provide damping. Values of additional capacitance and/or series resistance should be determined by using system studies.

As example, the following cases are illustrated in Figure F5:

Case no.1: Addition of a 195 nF capacitor across the reactor plus a total high frequency resistance in the resonant circuit (at the TRV frequency, sum of equivalent high frequency series resistance in the current-limiting reactor and in the parallel capacitor) of 47.6Ω. This case allows the use of a line system class circuit-breaker since the resulting TRV is below the rated TRV envelope.

Case no.2: Addition of a 195 nF capacitor to ground on the load side reactor terminal, plus a total high frequency resistance in the resonant circuit (at the TRV frequency, sum of equivalent high frequency series resistance in the current-limiting reactor and in the shunt capacitor) of 47.6Ω. This case allows the use of a line system class circuit-breaker since the resulting TRV is below the rated TRV envelope.

Case no.3: Addition of a 1.20 µF capacitor to ground on the load side reactor terminal, plus a total high frequency resistance in the resonant circuit (at the TRV frequency, sum of equivalent high frequency series resistance in the current-limiting reactor and in the shunt capacitor) of 40Ω. This case allows the use of a cable system class circuit-breaker since the resulting TRV is below the rated TRV envelope.

Case no.4: Addition of a 1.95 µF capacitor across the coil, plus a total high frequency resistance in the resonant circuit (at the TRV frequency, sum of equivalent high frequency series resistance in the current-limiting reactor and in the parallel capacitor) of 17.0Ω. This case allows the use of a cable system class circuit-breaker since the resulting TRV is below the rated TRV envelope.

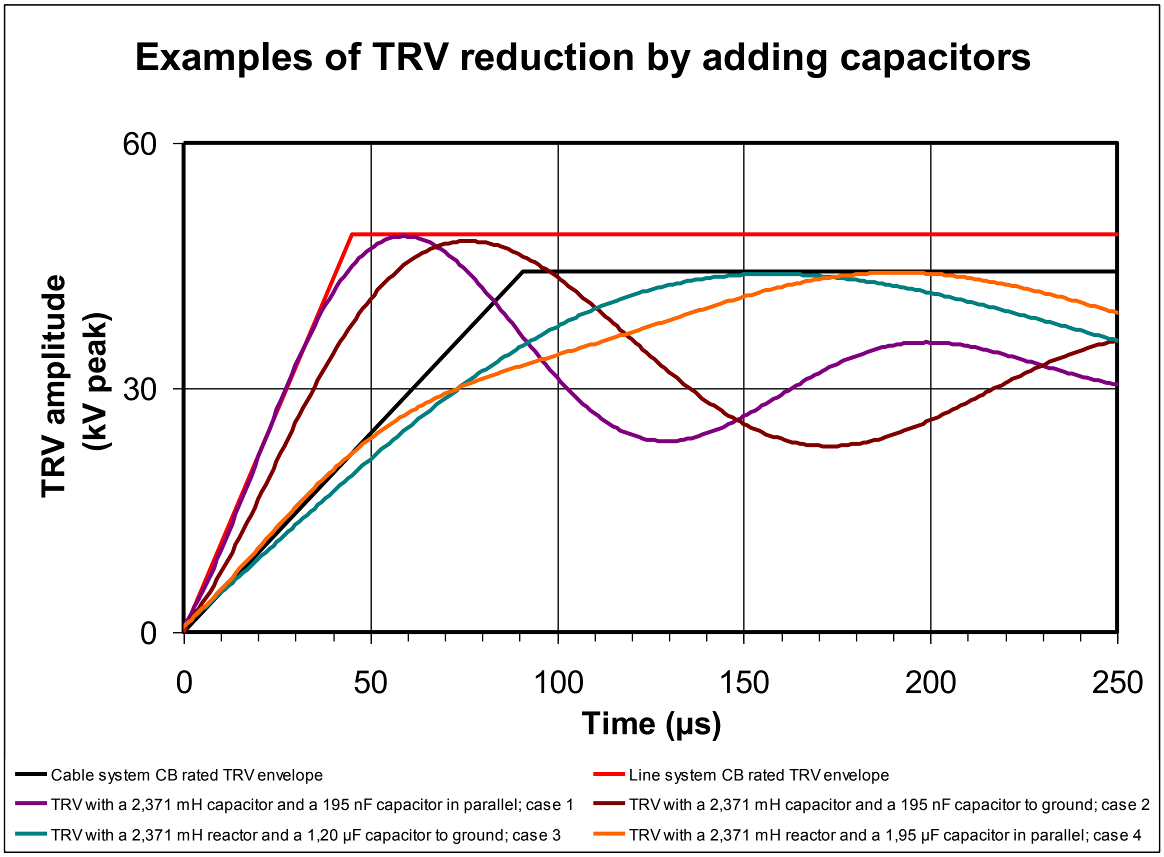


Figure F.5 Examples of TRV reduction by adding a capacitor across the current-limiting reactor or phase-to-ground, on the load side of the current-limiting reactor.

F.9 Mitigation

As can be seen in Figure E5, capacitors do effectively mitigate TRV problems caused by the addition of a current-limiting reactor. Capacitors are built by various manufacturers and are available for various system voltages and reactor ratings. Some are specially designed to be installed inside the reactor and there is no need to prepare a separate structure for installation. Others are "stand-alone" and may employ the same technology as is used in power capacitors or CVTs and coupling capacitors for power line carrier (PLC).

When designing a system incorporating a series reactor or installing a new series reactor in an existing system, it is strongly recommended to evaluate the resulting transient recovery voltage across the circuit-breakers in the system. If there is the risk of reaching a TRV which exceeds the TRV ratings of the circuit-breakers in use, a capacitor should be installed across the reactor or from the load side reactor terminal to ground.

It should be noted that if cable is used to connect a current-limiting reactor to the circuit breaker the cable capacitance to ground could be sufficient to ensure that there is no circuit breaker TRV problem. If further mitigation is required then the best solution is a capacitor across the reactor.

Proper sizing and location of TRV mitigation capacitor(s) requires a detailed system analysis. All the stray capacitances and damping elements should be taken into account. In most practical cases, system high frequency damping is high enough to reduce the first peak of the TRV below the breaker's TRV envelope. Typically, components in an actual system will provide better damping than what was assumed for the preceding example due to inherent characteristics such as "skin effect". Overhead transmission lines and underground cables connected to the bus provide the bulk of the damping resistance. It must be emphasized that a high frequency model of the series reactor should also be used to model the real damping in the system.

There might be some cases where the system inherent damping is not enough, and a study indicates that the first TRV peak exceeds the circuit breaker's capability. In such cases a damping resistor should be employed in series with the TRV mitigation capacitor.

A number of the references at the end of the annex provide background information and guidance.

F.10 Supporting Documentation

More information on CB TRV issues associated with the application of reactors and mitigation measures can be found in a number of sources; many of which are documented in the following listing. References include IEEE and IEC standards and guides, IEEE reference books and various technical papers.

[F1] ANSI/IEEE Std. C37.011-2005, "IEEE Application Guide for Transient Recovery Voltage for AC High Voltage Circuit-breakers".

[F2] Grigsby, L.L. "The Electric Power Engineering Handbook", CRC Press (in cooperation with IEEE Press); 2001.

[F3] Harlow, Janus H., "Electric Power Transformer Engineering", CRC Press (in cooperation with IEEE Press); 2004.

[F4] CIGRE Technical Brochure, "Transient Recovery Voltages in Medium Voltage Networks".

[F5] Swindler David L., Schwartz Paul, Harner Paul S. and Lambert Stephen R., "Transient Recovery Voltage Considerations in the Application of Medium Voltage Circuit-breakers", IEEE Transactions on Industry Applications, vol. 33, no. 2, March/April 1997.

[F6] Peelo D.F. et all, "Mitigation of Circuit Breaker Transient Recovery Voltages Associated with Current Limiting Reactors", IEEE Transactions on Power Delivery, vol. 11, no. 2, April 1996.

[F7} Lowe S.K., "Circuit Breaker Stresses Associated with H.V. Series Reactors", Australian Electrical Research, Canberra, May 10-12, 1972.

[F8] IEEE PC37.06/D6 AC High-voltage circuit breakers rated on a symmetrical basis – Preferred ratings and related required capabilities, October 2004.

[F9] IEEE C37.015 1993 (R2000) IEEE Application Guide for Shunt Reactor Switching.

[F10] ANSI C37.06.1-2000 Guide for High Voltage Circuit Breakers Rated on a Symmetrical Current Basis Designated "Definite Purpose for Fast Transient Recovery Voltage Times".

[F11] IEC 62271-110 High Voltage Switchgear and Controlgear Part 110: Inductive Load Switching.

[F12] IEC 62271-100 Ed.2; Alternating-current circuit-breakers

[F13] CIGRE WG A3.11 Guide for application of IEC 62271-100 and IEC 62271-1 (2006)

[F14] IEEE C37.010-1999, IEEE Application Guide for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis (ANSI).

[F15] J. Carr, L.V. McCall, "Divergent Evolution and Resulting Characteristics Among the World's Distribution Systems", IEEE Tranactions on Power Delivery, July 1992, Volume 7, Issue 3.

Annex G

(informative)

Bibliography

[B1] Braunovic, M., "Effect of contact aid compounds on the performance of bolted aluminum-to-aluminum joints under load cycling conditions," *IEEE Transactions on Components, Hybrids and Manufacturing Technology,* vol. CHMT-9, no. 1, pp. 59-70, Mar. 1986.

[B2] Braunovic, M., "Evaluation of different platings for aluminum-to-copper connections," Electrical Contacts-1991. *Proceedings of the 34th IEEE/HOLM Conference on Electrical Contacts,* Chicago, Ill., pp. 249-260, Oct. 1991.

[B3] Braunovic, M., "Evaluation of different types of contact air compounds for aluminum-to-copper connections," Electrical Contacts-1990. *Proceedings of the 15th Conference on Electrical Contacts,* Montreal, Quebec, Canada, pp. 509-517, Aug. 1990.

[B4] Deutsch, F., "Measuring the Active Power Losses of Large Reactors," *Brown Boveri Review,* vol. 47, pp. 268-278, Apr. 1960.

[B5] Hemmes, R. T. and Graham, D. C., "Measurement of self-cooled transformer sound levels in relatively high ambients," *IEEE Transactions on Power Apparatus and Systems,* vol. PAS-89, pp. 1657-1662, Sept./Oct. 1970.

[B6] Jackson, R. L., "Significance of surface preparation for bolted aluminum joints," *IEE Proceedings, C, General Transmission and Distribution,* vol. 128, pp. 45-54, Mar. 1981.

[B7] Kusters, N. L. and Petersons, 0. A., "Transformer-ratio-arm bridge for high voltage capacitance measurements," *IEEE Transactions (Communications and Electronics),* vol. 68, pp. 606-611, Nov. 1963.

[B8] Malewski, R., Anderson, W Ft.. and Moore, W. J. M., "Interlaboratory comparison of EHV shunt reactor loss measurements," *IEEE Transactions on Power Apparatus and Systems,* vol. PAS-99, no. 4, July/Aug. 1980.

[B9] Malewski, R., Arseneau, R., and So, E., "A comparison of instrumentation for measuring the losses of large power transformers," *IEEE Transactions on Power Apparatus and Systems,* vol. PAS-102, No. 6, pp. 1570-1573, June 1983.

[B 10] Moore, W. J. M., "A technique for calibrating power frequency wattmeters at very low power factors," *IEEE Transactions on Instrumentation and Measurement,* vol. IM-23, no. 4, pp. 318-322, Dec. 1974.

[B11] Moore, W. J. M. and Raftis, F. A., "Measurement of shunt reactor loss at high voltage with an alternating current comparator bridge," *IEEE Transactions on Power Apparatus and Systems,* vol. PAS-92, no. 2, pp. 662-667, Mar./Apr. 1973.

[B 12] Petersons, 0. A., "Transformer-ratio-arm bridge for measuring large capacitors above 100 volts," *IEEE Transactions on Power Apparatus and Systems,* vol. PAS-87, pp. 1354-1361, May 1968.

[B13] Uniform Building Code (UBC) 1997[8]

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[8] The Uniform Building Code is available from The International Code Council, Country Club Hills, at

[B14] IEEE 100, The Authoritative Dictionary of IEEE Standard Terms.

[B15] IEEE Std. 315, Graphic Symbols for Electrical and Electronics Diagrams (Including Reference Designation Letters) (ANSI).

[B16] IEC/TR 60943-1998, Guidance concerning the permissible temperature rise for parts of electrical equipment, in particular for terminals.

[B17] IEEE Std C57.12.80-2002, IEEE Standard Terminology for Power and Distribution Transformers (ANSI).

[B18] IEEE Std C57.12.90-2006, IEEE Standard Test Code for Liquid-Immersed Distribution, Power and Regulating Transformers.

[B19] IEEE Std C62.1-1989 (Reaff 1994), IEEE Standard for Gapped Silicon-Carbide Surge Arresters for AC Power Circuits (ANSI).

[B20] IEEE Std C62.2-1987, IEEE Guide for the Application of Gapped Silicon-Carbide Surge Arresters for Alternating-Current Systems (ANSI).

[B21] IEEE Std C62.11-2005, IEEE Standard for Metal-Oxide Surge Arresters for AC Power Circuits (> 1 kV).

[B22] IEEE Std C62.22-1997, IEEE Guide for the Application of Metal Oxide Surge Arresters for Alternating Current Systems (ANSI).

[B23] IEC 60076-8-1997, Power Transformer Application Guide.

[B24] IEEE Std C57.12.123 -2002, Guide for Transformer Loss Measurement.