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IEEE Standard for High-Voltage Testing Techniques

IEEE Power and Energy Society

Sponsored by the
Power System Instrumentation and Measurements Committee

IEEE
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USA

10 May 2013

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Power System Instrumentation and Measurements Committee
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Approved 6 March 2013

IEEE-SA Standards Board

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Abstract: Standard methods and basic techniques for high-voltage testing applicable to all types of apparatus for alternating voltages, direct voltages, lightning impulse voltages, switching impulse voltages, and impulse currents are established in this standard. Sections that deal with alternating voltage, direct voltage, and impulse testing are combined in this revision to organize the technical content for ease of use. In addition, the concept of measurement uncertainty in evaluation of high-voltage and high-current tests is introduced in this version.

Keywords: atmospheric corrections, high-current testing, high-voltage measurements, high-voltage testing, IEEE 4™, impulse currents, impulse voltages, testing

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Introduction

This introduction is not part of IEEE Std 4-2013, IEEE Standard for High-Voltage Testing Techniques.

The current revision of this standard is the eighth edition of this document as a separate standard. The subject had been addressed in the earliest standardization report of the American Institute of Electrical Engineers (AIEE) in 1889 and had been substantially elaborated upon in the subsequent reports issued from 1902 to 1933. When it was decided, in 1922, to reorganize the AIEE's standards into separate sections, the measurement of test voltages became one of the first subjects to be designated for a separate publication. The first edition was published in 1928.

This standard establishes standard methods and basic techniques for high-voltage testing. The standard is applicable to all types of apparatus for alternating voltages, direct voltages, lightning impulse voltages, switching impulse voltages, and impulse currents.

The following standards have been used to prepare this document:

IEC 60052, Recommendations for voltage measurement by means of standard air gaps.

IEC 60060-1, High-voltage test techniques—Part 1: General definitions and test requirements.

IEC 60060-2, High-voltage test techniques—Part 2: Measuring systems.

IEC 60060-3, High-voltage test techniques—Part 3: Definitions and requirements for on-site testing.

IEC 60270, Partial discharge measurements.

IEC 60507, Artificial pollution tests on high-voltage insulators to be used on a.c. systems.

IEC 61083-1, Instruments and software used for measurement in high-voltage impulse tests—Part 1: Requirements for instruments.

IEC 61083-2, Digital recorders for measurements in high-voltage impulse tests—Part 2: Evaluation of software used for the determination of parameters of impulse waveforms.

IEC 61245, Artificial pollution tests on high-voltage insulators to be used on d.c. systems.

IEC 62475, High-current test techniques: Definitions and requirements for test currents and measuring systems.

ISO/IEC Guide 98-3, Uncertainty of measurement—Part 3: Guide to the expression of uncertainty in measurements (GUM).

For ease of use, this revision organizes the technical content in such a way as to combine sections that deal with alternating voltage, direct voltage, and impulse voltage testing. In addition, this version introduces the concept of measurement uncertainty in evaluation of high-voltage and high-current tests.

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1. Overview

1.1 Scope

This standard is applicable to:

- Dielectric tests with direct voltages
- Dielectric tests with alternating voltages
- Dielectric tests with impulse voltages
- Tests with impulse currents
- Tests with combinations of the above
- Capacitance and dielectric loss measurements

This standard is applicable only to tests on equipment with a rated voltage above 1000 V.

Procedures are given for applying correction factors to convert test data to standard atmospheric conditions.

This standard also specifies procedures for testing equipment when external insulation of the test object is to be subjected to dry, wet, or contaminated conditions.

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1.2 Purpose

The purpose of this standard is to:

— Define terms of general applicability

— Present general requirements regarding test equipment and procedures

— Describe methods for evaluation of test results

1.3 Application

The methods of measurement and testing techniques described in this standard are generally applicable to all types of apparatus. Alternative test procedures may be required or permitted by the relevant apparatus committee standards.

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 the 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/IEEE C2 National Electrical Safety Code (NESC).

ANSI/IEEE Std 510™-1983, IEEE Recommended Practices for Safety in High-Voltage and High-Power Testing.

IEC 60270, High-Voltage Test Techniques—Partial discharge measurements.

IEC 61083-1, Instruments and software used for measurement in high-voltage impulse tests—Part 1: Requirements for instruments.

NFPA 70E—Standard for Electrical Safety in the Workplace.

3. Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause. [1]

accuracy: The degree of agreement between a measured value and the true value.

approved measuring system: A measuring system that is shown to comply with one or more of the sets of requirements described in this standard by:

— an initial acceptance test
— successive performance checks and performance tests
— inclusion of the results of these tests in the record of performance[2]

[1] *IEEE Standards Dictionary Online* subscription is available at:
http://www.ieee.org/portal/innovate/products/standard/standards_dictionary.html.

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assured disruptive discharge voltage: The prospective value of the test voltage that causes disruptive discharge under specified conditions.

conventional deviation of the disruptive discharge voltage (*z*): The difference between the 50% and 16% disruptive discharge voltages.

NOTE— It is often expressed in per unit or percentage value referred to the 50% disruptive discharge voltage.

dielectric loss factor: The factor by which the product of a sinusoidal alternating voltage applied to a dielectric and the component of the resulting current having the same period as the voltage have to be multiplied in order to obtain the power dissipated in the dielectric.

discharge: The passage of electricity through gaseous, liquid, or solid insulation.

disruptive discharge: A discharge that completely bridges the insulation under test, reducing the voltage between the electrodes practically to zero. Syn: electrical breakdown.

disruptive discharge probability (*p*): The probability that one application of a prospective voltage of a given shape and type will cause a disruptive discharge.

disruptive discharge voltage: The voltage causing the disruptive discharge for tests with direct voltage, alternating voltage, and impulse voltage chopped at or after the peak; the voltage at the instant when the disruptive discharge occurs for impulses chopped on the front.

error: The difference between the measured value of a quantity and the true value of that quantity under specified conditions.

external insulation: The air insulation and the exposed surface of the solid insulation of a piece of equipment, which are subject to both electrical stress and the effects of atmospheric and other conditions such as contamination, humidity, vermin, etc.

fifty percent disruptive discharge voltage (V_{50}): The prospective value of the test voltage that has a 50% probability of producing a disruptive discharge.

flashover: A disruptive discharge over the surface of a solid insulation in a gas or liquid.

impulse: An intentionally applied transient voltage or current that rises rapidly to a peak value and then falls more slowly to zero.

internal insulation: Insulation comprising solid, liquid, or gaseous elements, which are protected from the effects of atmospheric and other external conditions such as contamination, humidity, vermin, etc.

nondisruptive discharge: A discharge between intermediate electrodes or conductors in which the voltage across the terminal electrodes is not reduced to practically zero.

nonself-restoring insulation: Insulation that loses its insulating properties or does not recover them completely after a disruptive discharge.

nonsustained disruptive discharge: A momentary disruptive discharge.

partial discharge: A discharge that does not completely bridge the insulation between electrodes.

[2] The system is approved only for the arrangements and operating conditions included in its record of performance.

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***p*-percent disruptive discharge voltage (V_p):** The prospective value of the test voltage that has a *p*-percent probability of producing a disruptive discharge.

prospective characteristics of a test voltage causing disruptive discharge: The characteristics of a test voltage that would have been obtained if no disruptive discharge had occurred.

puncture: A disruptive discharge through solid insulation.

random error: The result of a measurement minus the mean that would result from an infinite number of measurements of the same measurand carried out under repeatable conditions.

NOTE 1—Random error is equal to error minus systematic error.

NOTE 2—Because only a finite number of measurements can be made, it is possible to determine only an estimate of random error.

record of performance of a measuring system: A detailed record, established by the user, describing the system and containing evidence that the requirements given in this standard have been met. This evidence shall include the results of the initial acceptance test and the schedule and results of each subsequent performance test and performance check.

reference measuring system: A measuring system having sufficient accuracy and stability for use in the approval of other systems when making simultaneous comparative measurements with specific types of waveforms and ranges of voltage.

NOTE—A reference measuring system (maintained according to the requirements of this standard) can be used as an approved measuring system, but the converse is not true.

response time (*T*): A quantity that is indicative of the speed with which a system responds to changing voltages or currents.

scale factor of a measuring system: The factor by which the output indication is multiplied to determine the measured value of the input quantity or function.

self-restoring insulation: Insulation that completely recovers its insulating properties after a disruptive discharge.

sparkover: A disruptive discharge between electrodes in a gas or liquid.

standard deviation of the disruptive discharge voltage of a test object (*s*): A measure of the dispersion of the disruptive discharge voltage estimated by:

$$s = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(V_i - V_a)^2}$$

where

V_i is the i^{th} measured disruptive discharge voltage

V_a is the arithmetic mean of the disruptive discharge voltages (in most cases it is identical to V_{50})

n is the number of observations (discharges)

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NOTE 1—It can also be evaluated by the difference between the 50% and 16% disruptive discharge voltages (or between the 84% and 50% disruptive discharge voltages). It is often expressed in per unit or percentage value referred to the 50% disruptive discharge voltage.

NOTE 2—For successive disruptive discharge tests, the standard deviation s is defined by the above formula. For multiple level up-and-down tests, it is defined by the difference of the quantiles. The methods are equivalent because, between $p = 16\%$ and $p = 84\%$, all probability distribution functions are nearly equal.

step response *g(t)*: The normalized output as a function of time t when the input is a voltage or current step.

surge: A transient voltage or current, which rises rapidly to a peak value and then falls more slowly to zero, occurring in electrical equipment or networks in service.

systematic error: The mean that would result from an infinite number of measurements of the same measurand carried out under repeatable conditions minus a true value of the measurand.

NOTE 1—Systematic error is equal to error minus random error.

NOTE 2—Like true value, systematic error and its causes cannot be completely known.

transfer function *H(f)*: The quantity $Y(f)$ divided by $X(f)$, where $Y(f)$ and $X(f)$ are the frequency domain representations of the output and input signals respectively.

type A evaluation of uncertainty: A method of evaluation of uncertainty by the statistical analysis of a series of observations.

type B evaluation of uncertainty: A method of evaluation of uncertainty by means other than the statistical analysis of a series of observations.

uncertainty: An estimated limit based on an evaluation of the various sources of error.

undershoot: The peak value of an impulse voltage or current that passes through zero in the opposite polarity of the initial peak.

voltage ratio of a voltage divider: The factor by which the output voltage is multiplied to determine the measured value of the input voltage.

withstand probability (*q*): The probability that one application of a prospective voltage of a given shape and type will not cause a disruptive discharge.

withstand voltage: The prospective value of the test voltage that equipment is capable of withstanding when tested under specified conditions.

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4. Safety Awareness

WARNING

For all tests involving hazardous voltage levels, special attention shall be paid to ensure the safety of all personnel. Personnel safety is of utmost importance during all testing procedures. All equipment tests shall be performed on de-energized and isolated systems. Appropriate safety practices shall be followed. Where applicable, the safety practices shall include, but not be limited to, the following requirements:

1) Applicable user safety operating procedures.

2) ANSI/IEEE Std 510-1983, IEEE Recommended Practices for Safety in High-Voltage and High-Power Testing.

3) ANSI/IEEE C2 National Electrical Safety Code (NESC).

4) NFPA 70E—Standard for Electrical Safety in the Workplace.

5) Applicable national, state and local safety operating procedures.

6) Protection of utility and customer property.

5. General requirements for high-voltage tests and measurements

5.1 Normal environmental conditions

For high-voltage testing, in addition to a clean and dry environment, the following conditions are considered normal:

Temperature:	10 °C to 40 °C
Relative humidity:	less than 95% non-condensing
Altitude:	less than 1000 m

High-voltage tests and measurements performed in other than normal conditions may require special equipment and considerations.

5.2 Arrangement of the test object

5.2.1 General arrangement

The electrical discharge characteristics of a test object may be affected by its general arrangement. For example, its clearance from other energized or grounded structures, its height above ground level, and the arrangement of the high-voltage lead may affect the disruptive discharge voltage. For this reason, the general arrangement should be specified by the relevant apparatus standard.

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5.2.2 Clearances

A clearance to nearby structures equal to or greater than 1.5 times the length of the shortest possible discharge path on the test object usually makes proximity effects negligible.

In wet or contamination tests, or whenever the voltage distribution along the test object and the electric field around its energized electrode are sufficiently independent of external influences, smaller clearances may be acceptable, provided that discharges do not occur to nearby structures.

For positive polarity switching impulses, conservative clearances may be obtained from the relationship between the critical sparkover voltages of rod-plane gaps, and the gap spacing:

$$V_{50} = \frac{3400}{(1 + \frac{8}{d})} \quad (1)$$

where

V_{50} is the critical sparkover voltage (in kilovolts)
d is the gap spacing (in meters)

If the standard deviation of the assumed normal probability distribution is taken as 5% of V_{50}, the withstand voltage at three standard deviations below the 50% level is given by:

$$V_{WS} = 0.85 \times V_{50} \quad (2)$$

where

V_{WS} is the withstand voltage corresponding to a sparkover probability of 0.16%

Equation (1) and Equation (2) may then be used to determine the appropriate clearance to withstand a given voltage level. Alternatively, the curves given in Figure 1 may be used.

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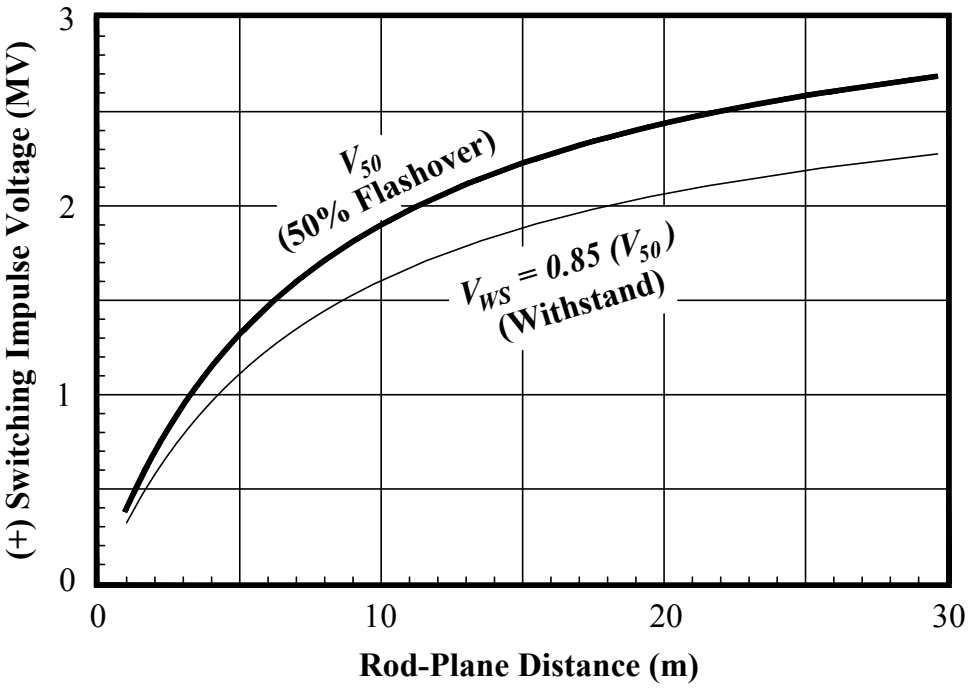


Figure 1—Voltage versus distance for rod-plane gap

5.3 Grounding requirements for high-voltage tests

There are normally several points in the test circuit that are interconnected and connected to the ground terminal of the test object. It is important that the impedance to ground and the impedance between such points in the test circuit be kept low to minimize potential differences during breakdowns. This can be accomplished through the use of single-point grounding, through the use of large nonmagnetic metal sheets between the ground terminals of the various components of the circuit, or by making short ground connections to a large metal sheet or mesh either on, or built into, the floor of the test area.

Normal practice is to locate the single-point ground of the test circuit at the base of the high-voltage divider, or the point of voltage measurement.

5.4 Use of properly dimensioned interconnections and electrodes

The position and dimensions of the interconnecting leads and electrodes used in the high-voltage test circuit may influence the performance of the measuring system or the results of the test.

a) For alternating and direct voltage tests, a conductor diameter of 2.5 cm (1 in) per 100 kV test voltage is usually adequate.
b) For all negative polarity impulses, and positive polarity lightning impulses below 1000 kV, small diameter conductors (wires) can be used.
c) For positive polarity impulses above 1000 kV, larger diameter conductors are usually required to control streamer discharges.

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d) For positive polarity switching impulses, conductor diameters should be chosen to limit the surface electric field strength to less than 15 kV/cm (38 kV/in).

5.5 Susceptibility to noise: instrumentation shielding

5.5.1 General

The shielding of general-purpose instruments may not be adequate for use in high-voltage laboratories. Interference may be induced by the transient electromagnetic field or conducted by either the signal or the supply lines. Interference may attain high levels, especially in the case of chopped impulses.

5.5.1 Precautions

5.5.1.1 Electromagnetic shielding

Interference due to electromagnetic fields penetrating directly into the instrument may be reduced by placing the instrument in a Faraday cage having sufficient attenuation in the frequency range of interest. Such a Faraday cage consists of a metal enclosure, which insures conductivity across permanent and mobile joints. This metal enclosure may be a shielded control room or an instrument enclosure. In most cases, the Faraday cage should be solidly grounded at a single point.

5.5.1.2 Reduction of conducted interference from the supply line

Conducted interference of the mains supply can be reduced by inserting a filter (effective in the range from some tens of kilohertz to some tens of megahertz). Another means of reducing conducted interference is to use an isolating transformer with low inter-winding capacitance between the instrument and the mains supply, or, for even better noise attenuation, an electrostatic shield between the windings.

5.5.1.3 Reduction of interference on the signal line

Interference due to current flowing in the shield of the measuring cable may be reduced by adequate grounding at the voltage divider side, by using tri-axial cable with the outer shield grounded at both input and instrument ends, and/or by cable running through a metallic conduit connected at both ends to the local grounds. Inner and outer shields should be bonded at the input end. Avoiding loops between the measuring cable and the ground returns can also reduce interference.

Interference due to potential difference, induced or applied between the terminals of the measuring cable, may be reduced by using an input voltage as high as possible, namely by operating the instrument on its maximum range, or by inserting an external attenuator between the receiving end of the cable and the instrument.

Interference may also be reduced in measurements by using optical transmission systems, provided that the converters at each end are well shielded, and not sensitive to temperature effects.

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5.6 Classification of measuring systems

High-voltage measuring systems are classified in terms of their overall uncertainty. There are two basic classifications of measuring systems identified by this standard. These are:

a) Approved measuring systems.

b) Reference measuring systems.

The uncertainty requirements for each class of measuring system are summarized in Table 1, and are further discussed in 5.6.1 and 5.6.2.

Table 1—Basic uncertainty requirements by measuring system classification

Measured Quantity	Approved measuring system	Reference measuring system
Direct voltage (arithmetic mean value)	± 3%	± 1%
Alternating voltage [peak or root mean square (rms) value]	± 3%	± 1%
Impulse voltage peak (peak value for full or tail-chopped impulses)	± 3%	± 1% (see Note, below)
Impulse voltage time parameters (front time and time to half-value)	± 10%	± 5%

NOTE—When measuring front-chopped impulses with a reference measuring system, the overall uncertainty requirement for peak value measurement is relaxed to ± 3%, per 5.6.2.1.3.

5.6.1 Approved measuring systems

Approved measuring systems as defined and described in Clause 3, Clause 6, Clause 7, Clause 8, and Clause 9 shall be used for making routine high-voltage measurements.

5.6.1.1 Requirements for approved measuring systems

5.6.1.1.1 Alternating voltage

An approved measuring system shall be capable of measuring the peak or root mean square (rms) value of an alternating voltage with an overall uncertainty of not more than ± 3% in its range of use. More detailed information on approved measuring systems for alternating voltage may be found in 6.3.

5.6.1.1.2 Direct voltage

An approved measuring system shall be capable of direct voltage measurement with an overall uncertainty of not more than ± 3% in its range of use. More detailed information on approved measuring systems for direct voltage may be found in 7.3.

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5.6.1.1.3 Lightning and switching impulse voltage

An approved measuring system shall be capable of full and tail-chopped impulse voltage measurement with an overall uncertainty of not more than ± 3% for peak voltage, and not more than ± 10% for time parameters, in its range of use. More detailed information on approved measuring systems for impulse voltage may be found in 8.3.

5.6.2 Reference measuring systems

Reference measuring systems as defined in Clause 3 and Clause 5 are normally used to calibrate approved measuring systems. Reference measuring systems may be used for making routine high-voltage measurements if it is shown through appropriate performance tests and performance checks that such use does not affect their performance.

5.6.2.1 Requirements for reference measuring systems

5.6.2.1.1 Alternating voltage

A reference measuring system shall be capable of measuring the peak or rms value of an alternating voltage with an overall uncertainty of not more than ± 1% in its range of use.

5.6.2.1.2 Direct voltage

A reference measuring system shall be capable of direct voltage measurement with an overall uncertainty of not more than ± 1% in its range of use.

5.6.2.1.3 Lightning and switching impulse voltage

A reference measuring system shall be capable of full impulse voltage measurement with an overall uncertainty of not more than ± 1% of peak voltage for full and tail-chopped impulses, not more than ± 3% of peak voltage for front-chopped impulses, and not more than ± 5% for time parameters, in its range of use.

5.6.2.2 Calibration of reference measuring systems

The compliance of a reference measuring system with the relevant requirements given in 5.6.2.1 of this standard shall be shown by the test outlined in 5.6.2.2.1. Alternatively the test outlined in 5.6.2.2.2 may be used.

5.6.2.2.1 Reference method: comparative measurement

The satisfactory performance of a reference measuring system shall be shown by making simultaneous comparative measurements of appropriate waveshapes with a suitable standard measuring system with overall uncertainty traceable through national or international comparisons.

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5.6.2.2.2 Alternative method for impulse voltages: measurement of scale factor and evaluation of step response parameters

The scale factor of a reference measuring system shall be established for one impulse voltage shape by making simultaneous comparative measurements with a suitable standard measuring system with overall uncertainty traceable through national or international comparisons.

The step response parameters shall then be evaluated according to Annex B and shall satisfy the parameters specified in 8.7 of this standard.

5.7 Procedures for qualification and use of measuring systems

5.7.1 General principles

Approved measuring systems are required to undergo an acceptance test followed by performance tests and performance checks throughout their service lives. These performance tests and checks shall prove that the measuring system can measure the intended test voltages and currents within the uncertainties specified in this document, and that these uncertainties are traceable to national and international standards.

The following are necessary:

a) Acceptance test on the system or system components.

b) Performance tests on the system (periodic, see 5.7.2).

c) Performance checks on the system (periodic, see 5.7.3).

The flowchart shown in Figure 2 outlines the process by which an approved measuring system shall be qualified and maintained.

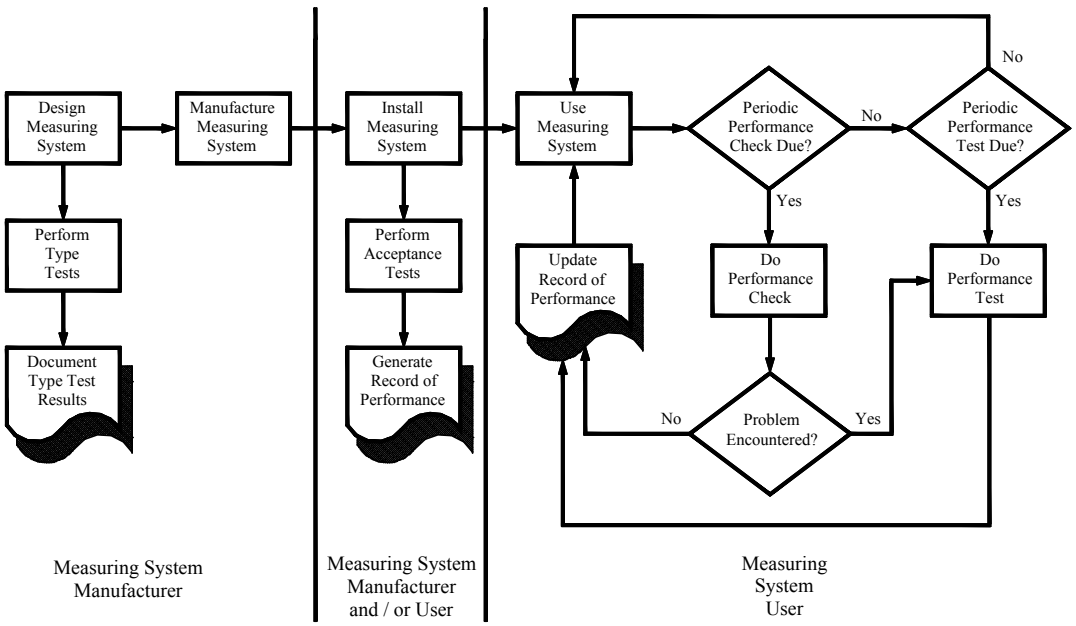


Figure 2—Qualification and maintenance of an approved measuring system

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A major requirement for converting devices, transmission systems, and measuring instruments used in measuring systems is stability within their specified range of operating conditions so that the scale factor of the measuring system remains constant over long periods. The scale factor is determined in the performance tests.

Test facilities shall use the tests given in this document to qualify their measuring system(s). Alternatively, any test facility may choose to have the performance tests made by a traceable calibration laboratory.

Calibrations performed by an ISO/IEC 17025 accredited laboratory for the quantities calibrated and reported under the accreditation are considered traceable to national and international standards. If other calibration laboratories are chosen, it is the responsibility of the user to ensure that calibrations are performed by competent personnel using suitable reference measuring systems and procedures, and that proper traceability of the reference equipment has been ensured.

5.7.2 Schedule of performance tests

To maintain the quality of a measuring system, its scale factor(s) shall be determined by the performance tests repeated periodically as required in the record of performance. It is recommended that the performance tests should be repeated annually, or as required based on historical data.

Performance tests shall be made after major repairs to the measuring system and whenever a circuit arrangement that is beyond the limits already given in the record of performance is to be used.

When performance tests are required because a performance check shows that the scale factor has changed significantly, the cause of this change shall be investigated before the performance tests are made.

5.7.3 Need for performance checks

Performance checks should be performed by the user at regular intervals to assist in assuring continued stability of the measuring system.

If the performance check results in a discrepancy from the expected results, a performance test shall be performed.

5.7.4 Requirements for the record of performance

All approved measuring systems require that a record of performance be generated and maintained to document the accuracy and stability of the system. The required content of the record of performance for the various measurement systems covered by this standard is specified in the respective clauses.

The results of all tests with the conditions under which the results were obtained shall be kept in the record of performance (electronically stored or stored in paper format) established and maintained by the user. The record of performance shall uniquely identify the components of the measuring system and shall be structured so that performance of the measuring system can be traced over time.

The record of performance shall be comprised of at least the following chapters:

a) General description of the measuring system.

b) Results of acceptance test on the converting device, transmission system(s) and measuring instrument(s).

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c) Results of routine test(s) on the measuring system, when performed.

d) Results of consecutive performance tests on the measuring system.

e) Results of consecutive performance checks on the measuring system (optional).

NOTE—In general, a description is given for the measuring system, including main data and capabilities of the measuring system, such as the rated voltage or current, waveform(s), range of clearances, operating time, or maximum rate of voltage applications. For many measuring systems, information on the transmission system and grounding arrangements are important. When needed, a description is also given of the components of the measuring system, including, for example, the measuring instrument type and identification.

5.7.4.1 Exceptions

In the case of apparatus or equipment manufactured before the date of issue of this standard, if the evidence required in some part(s) of the acceptance test is not available, then performance tests and checks made in accordance with earlier versions of this standard are deemed to be adequate, provided they show that the scale factor is stable. The results of these previous checks shall also be entered in the record of performance.

If equipment manufactured before the date of issue of this standard is repaired, it is recommended that an acceptance test be conducted and included in the record of performance.

Approved measuring systems comprised of several pieces of equipment used interchangeably may be covered by a single record of performance including all possible combinations, with the least amount of duplication possible. Specifically, each converting device shall be covered individually, but transmission systems and instruments may be covered generically so that a range of cable lengths or similar instruments that meet the requirements of the relevant apparatus standard may be indicated.

5.7.5 Uncertainty

A measuring system qualified under this document shall be evaluated for the uncertainties that are related to the measurement. Guidance on determining uncertainty contributions that need to be considered, and on their combination, is given in 5.7.6.8 and Annex D.

It is emphasized that *uncertainty* is the envelope of the difference between the measured value and the true value. This should be distinguished from *tolerance,* which is the permitted difference between the specified value and the measured value.

5.7.6 Tests and test requirements for an approved measuring system and its components

A high-voltage or high-current measuring system is generally comprised of the following:

a) A converting device (e.g., a voltage divider, high-voltage measuring impedance, or shunt).

b) The leads required for connecting this device into the test circuit.

c) A measuring cable, together with any attenuating, terminating, and adapting impedances or networks.

d) The indicating or recording instrumentation.

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Measuring systems that utilize only some of the above components, or those that are based on different principles, may be acceptable. All measuring systems shall meet the requirements of this standard in order to be accepted.

The scale factor of the measuring system is determined by calibration according to the specified performance tests. For an impulse measuring system, the performance tests also show that its dynamic performance is adequate for the specified measurements and that the level of any disturbance is less than the specified limits. The equipment calibration should preferably be performed by comparison with a reference measuring system. If a measuring system is sensitive to proximity effects, the scale factor shall be measured for each condition of use. Each set of clearances or range of clearances shall be entered in the record of performance.

The input voltage or current used for calibration should be of the same type, frequency, or waveform as the quantity to be measured. The preferred calibration method for determining the scale factor of a measuring system is comparison with a reference measuring system at the maximum measured voltage or current. However, as reference-measuring systems are not always available at the highest voltages or currents, the comparison may be made at levels as low as 20% of the maximum measured quantity, provided that linearity is proven over the range of use.

Alternatively, the scale factor may be determined by measuring the scale factor of each component, usually at low voltage, and taking the product of the scale factors of the components (see 5.7.6.1.2), provided that the linearity has been proven over the range of use. When determining the system scale factor using low-voltage methods, the impedance of any measuring instrument used must be considered to allow for loading effects.

All equipment used in establishing the scale factor(s) of measuring systems and all instruments used in measuring systems shall have traceable calibration(s). The conditions under which the calibration has been performed shall be included in the record of performance. Whether the scale factor is determined by the reference method or an alternative method, the uncertainty must be evaluated (see 5.7.6.8 and Annex D).

5.7.6.1 Calibration – determination of the scale factor

The preferred method to determine the scale factor for a complete measuring system is by comparison with a reference measuring system. The scale factor of a measuring system can also be obtained as the product of the scale factors of its components.

5.7.6.1.1 Calibration of measuring systems by comparison with a reference measuring system (reference method)

The reference method is the preferred calibration method. A reference measuring system of sufficient rated measuring voltage or current shall be connected in parallel with the measuring system to be calibrated. Simultaneous readings shall be taken on both systems. The value of the input quantity obtained for each measurement by the reference measuring system is divided by the corresponding reading of the instrument in the system under test to obtain a value F_i of its scale factor. The procedure is repeated x times at each of L=5 levels (minimum and maximum of the operating range and three approximately equally spaced levels) to obtain the mean value F_m of the scale factor of the system under test:

$$F_m = \frac{1}{xL}\sum_{i=1}^{xL} F_i \tag{3}$$

The mean value F_m is taken as the scale factor. If the reference measuring system does not allow a calibration up to the rated measuring voltage or current of the system under calibration, a linearity test has

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to be added (see 5.7.6.2) to show that the scale factor is applicable over the full operating voltage or current range. The standard deviation of the individual values is given by:

$$s = \sqrt{\frac{1}{xL-1}\sum_{i=1}^{xL}(F_i - F_m)^2} \quad (4)$$

This results in the type A standard uncertainty of the comparison.

$$u_A = \frac{s}{\sqrt{xL}} \quad (5)$$

The uncertainty of the reference measuring system and the type B uncertainty contributions described in Annex D should be considered in the evaluation of the uncertainty of the calibration.

NOTE 1—Usually no more than x=10 independent readings are necessary.

NOTE 2—A rounded value F_o may be taken as the scale factor if the difference between F_o and F_m is introduced as an uncertainty contribution of type B.

NOTE 3—For measurement of direct and alternating voltages, independent readings may be obtained either by applying the test voltage and taking x readings, or by applying the test voltage x times and taking a reading each time. For impulses, x impulses are applied.

A measuring system with several scale factors (for example, a voltage divider with several low-voltage arms) shall be calibrated for each scale factor. Measuring systems with secondary attenuators may be calibrated on one setting only, provided that the load on the output of the converting device can be shown to be constant for all settings by other tests. For such cases, the full range of secondary attenuators shall be calibrated separately.

5.7.6.1.2 Calibration of components (alternative method)

The determination of the scale factor of a component may be made by one of the following methods:

a) By comparison with a reference component (e.g., a voltage divider with a reference voltage divider).
b) Simultaneous measurements of its input and output quantities.
c) A bridge method.
d) Calculation based on measured impedances.

Further tests on measuring systems, transmission systems (other than cables), and measuring instruments shall be made in accordance with tests described in 5.7.6.2, 5.7.6.3, 5.7.6.4, 5.7.6.5, 5.7.6.6, 5.7.6.7, 5.7.6.8, and 5.7.6.9.

The scale factor of the measuring system shall be determined as the product of the scale factors of its converting device, its transmission system, any secondary attenuator, and its measuring instrument. For the converting device and the transmission system or their combination, the scale factor shall be measured by

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one of the methods given in 5.7.6.1. The scale factor of an impulse measuring instrument is determined according to IEC 61083-1 (listed in Clause 2).

5.7.6.2 Linearity test

This test is intended to provide an extension of the validity of the scale factor from the maximum level at which a calibration has been carried out, over the full range of use. The output of the measuring system shall be compared with a device or system that is linear over the full range of use.

The ratio of readings between the measuring system and the comparison device or system shall be established for five voltages, ranging from the maximum operating voltage down to the voltage at which the scale factor has been determined.

Evaluation of linearity is based on the maximum deviation of the ratios R_i from the mean R_m of the five ratios of the measured voltage to the corresponding voltage of the comparison device. The maximum deviation is taken as a type B estimate of the standard uncertainty related to constancy of scale factor:

$$u_{B1} = \frac{1}{\sqrt{3}} \max_{i=1}^{5} \left| \frac{R_i}{R_m} - 1 \right| \tag{6}$$

Methods for determining linearity are given in Clause 6, Clause 7, Clause 8, and Clause 9 for each type of measuring system.

5.7.6.3 Dynamic behavior

The response of a component or a measuring system shall be determined in conditions representative of its use, particularly clearances to grounded and energized structures. Either the amplitude/frequency response (direct or alternating voltages) or the scale factors and time parameters at the limits of the range of use shall be measured.

The maximum deviation of the scale factor over the frequency range of use delivers a type B estimate of the standard uncertainty related to the dynamic behavior:

$$u_{B2} = \frac{1}{\sqrt{3}} \max_{i=1}^{5} \left| \frac{F_i}{F_m} - 1 \right| \tag{7}$$

where

F_i are the individual ratios

F_m is the mean ratio for parameters within the range of use

One method to determine dynamic behavior is to apply a sinusoidal input of known amplitude, usually at low level, and measure the output. This measurement is repeated for an appropriate range of frequencies. The deviations of the scale factor are evaluated according to the above formula.

Another method to determine dynamic behavior is to apply a unit step input, and record the output response. See Annex B for more information on this method.

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5.7.6.4 Short term stability test

The maximum operating voltage or current shall be applied to the device continuously (or, in the case of impulses, at the maximum rate) for a period appropriate to the anticipated use. The scale factor shall be measured before and immediately after (within 10 minutes) the application of the voltage or current.

The result of the test may be the change of scale factor from which the standard uncertainty contribution is estimated as a type B estimate:

$$u_{B3} = \frac{1}{\sqrt{3}} \left| \frac{F_{after}}{F_{before}} - 1 \right| \tag{8}$$

where

F_{before} and F_{after} are the respective scale factors before and after the short-term stability test

5.7.6.5 Long term stability

The long-term stability characteristics may be taken from manufacturer's data or be demonstrated by successive performance tests.

The result of the estimation delivers a standard uncertainty contribution, which is estimated as a type B estimate:

$$u_{B4} = \frac{1}{\sqrt{3}} \left| \frac{F_{next}}{F_{previous}} - 1 \right| \tag{9}$$

where

$F_{previous}$ and F_{next} are the respective scale factors of two successive performance tests

5.7.6.6 Ambient temperature effect

The scale factor of a measuring system can be affected by ambient temperature. This can be quantified by tests or by computations based on properties of components. Details of tests or calculations shall be included in the record of performance. Temperature correction factors may be used in cases where the ambient temperature varies over a wide range. If the scale factor deviation due to temperature is greater than 1% over the normal range of temperature operation, corrections are required. Any temperature corrections to be used shall be listed in the record of performance.

The result of the test, or evaluation, is the deviation of scale factor from the calibrated one at calibration temperature. The standard uncertainty due to ambient temperature is the following type B estimate:

$$u_{B5} = \frac{1}{\sqrt{3}} \left| \frac{F_T}{F_{cal}} - 1 \right| \tag{10}$$

where

F_T is the scale factor at the considered temperature and F_{cal} is that at the calibration temperature

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NOTE—Self heating effect is covered by the short-term stability test.

5.7.6.7 Proximity effect

Variations of the scale factor or of a parameter of a device due to proximity effects can be determined by measurements performed for different distances of the device from grounded walls or energized structures.

The result of the test is the change of scale factor from which the standard uncertainty contribution is estimated as a type B estimate:

$$u_{B6} = \frac{1}{\sqrt{3}} \left| \frac{F_{max}}{F_{min}} - 1 \right| \tag{11}$$

where

F_{max} and F_{min} are the scale factors for maximum and minimum distances to other objects.

NOTE 1—Different values for u_{B6} may be given for different ranges of distances.

NOTE 2—Some test facilities may choose to approve their measuring systems for only a single set of distances, or for a few sets or ranges of distances.

NOTE 3—Test circuit electrodes and interconnections may contribute to variations in scale factor due to proximity effects.

5.7.6.8 Expanded uncertainty of the scale factor

A simplified procedure to determine the expanded uncertainty of the scale factor u_F is given here, assuming that:

a) There is no correlation between the components of uncertainty being combined.

b) Type B components of uncertainty are assumed to have a rectangular distribution.

c) There are at least three type B components of uncertainty being combined.

These assumptions lead to a procedure to evaluate the expanded uncertainty u_F of the scale factor F (see Annex D):

$$u_F = k u_c = 2\sqrt{u_A^2 + u_{B1}^2 + u_{B2}^2 + \ldots + u_{BN}^2} = 2\sqrt{u_A^2 + \sum_{i=1}^{N} u_{Bi}^2} \tag{12}$$

where

N = number of components of type B uncertainty included in the expanded uncertainty estimate

k = 2 coverage factor for a 95% confidence interval with a normal distribution

u_c = combined standard uncertainty of the scale factor determined by calibration

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The standard type A uncertainty u_A of the scale factor is given by:

$$u_A = \frac{s}{\sqrt{n}} \tag{13}$$

where

s = standard deviation of the total number of measurements (see 5.7.6.1.1)

n = total number of measurements taken (see 5.7.6.1.1)

and

$$n = Lx \tag{14}$$

The number N of type B uncertainty contributions may differ for the different measurement systems (see Clause 6, Clause 7, Clause 8, and Clause 9). More information on the type B contributions is given in Annex D.

5.7.6.9 Interference test (transmission system and instrument for impulse measurements)

The test shall be made on the measuring system, with its cable or transmission system short-circuited at its input terminals without changing the ground connections of the cable or transmission system. An interfering condition shall be produced at the input of the measuring system by a disruptive discharge with an impulse representative of voltage or current amplitude and shape to be applied, and the output shall be recorded.

The interference ratio shall be determined as the maximum amplitude of the measured interference divided by the output of the measuring system when measuring the test voltage or current.

For passing the interference test, the maximum amplitude of the measured interference shall be less than 1% of the output of the measuring system when measuring the test voltage or current. Interference greater than 1% is permitted provided it is shown that it does not affect the measurement.

6. Tests and measurements with alternating voltage

6.1 Terms used to characterize alternating voltage tests and measurements

peak value of alternating voltage: The maximum value, disregarding small high-frequency oscillations (greater than 10 kHz), such as those arising from partial discharges.

root-mean-square (rms) value of alternating voltage: The square root of the average of the square of the voltage values during a complete cycle.

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value of the test voltage for alternating voltage: The peak value divided by $\sqrt{2}$, or the rms value as defined by the relevant apparatus standard.

6.2 Source requirements

6.2.1 Requirements for the test voltage

6.2.1.1 General requirements

The test voltage applied to the test object shall be an alternating voltage having a frequency in the range of 45 Hz to 65 Hz, normally referred to as power-frequency voltage, unless otherwise dictated by apparatus-specific tests. Apparatus-specific tests may employ frequencies as low as 0.1 Hz, variable frequencies of 20 Hz to 300 Hz, or fixed frequencies between 100 Hz and 400 Hz.

The voltage waveshape should approximate a sinusoid with both half cycles closely alike, and it should have a ratio of peak-to-rms values equal to $\sqrt{2}$ within ± 5%. It can generally be assumed that this requirement will be met if the total harmonic distortion (THD) [B122]] does not exceed 5%.

For some test circuits or test objects, greater deviations may have to be accepted and guidance should be provided by the relevant apparatus standard. The presence of the test object, especially if it has nonlinear impedance characteristics or very high capacitance, may cause considerable deviation from a sinusoid.

6.2.1.2 Test voltage tolerance

If not otherwise specified by the relevant apparatus standard, the measured value of the test voltage shall be maintained within ± 3% of the specified level for tests of 5 minutes or less.

6.2.2 Generation of the test voltage

The test voltage is generally supplied by a transformer or a resonant circuit. The voltage in the test circuit should remain within the ± 3% tolerance in the presence of normal leakage currents. Nondisruptive discharges in the test circuit should not reduce the test voltage to such an extent and for such a time that the value of the test voltage is significantly affected.

6.2.2.1 Transformer source

High-voltage tests normally result in load currents with superimposed time varying leakage current pulses as voltage is increased. The magnitude and duration of the current pulses is influenced by the test arrangement, the conductors used to connect the test object, atmospheric conditions, the characteristics of the test source, and other factors. It is normal for the apparatus under test to produce some current pulses since the test voltages are much higher than the operational voltages and these devices often lack large electrodes and ground shields to keep the test object electrically quiet. Since the current pulses are of short duration, voltage drops may be unrecognized by conventional alternating voltage measuring systems. The voltage stability of an alternating voltage test system used in tests with time-varying leakage current pulses can be verified by using a voltage measuring system with sufficient bandwidth.

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For dry tests below 100 kV on samples of solid insulation, insulating liquids, or combinations of the two, a test source rated current of > 100 mA and a system (transformer, regulator, etc., or generator) short circuit impedance of < 20% is generally sufficient.

For dielectric tests above 100 kV on external self-restoring insulation (low capacitance test objects such as insulators, circuit breakers, and switches), a test source rated current of > 100 mA and a system short circuit impedance of < 20% is generally sufficient for dry tests where no streamers are present.

For dielectric tests above 100 kV, test system current ratings of 1 A and system short circuit impedances < 20% may be necessary if continuous streamers are encountered or if wet tests are performed. When continuous streamers are present, it is recommended that faster responding voltage measurements are made to ensure that the test voltage is held within the voltage drop limit for the duration of the test. Alternatively, counter measures such as increasing electrode diameters or using larger connecting conductors can be used to reduce the streamers.

Short duration current pulses encountered at any test voltage are mostly supplied from the charge stored in capacitance in the test circuit. It is recommended that for tests above 100 kV a circuit capacitance greater than or equal to 1,000 pF be installed.

For tests under artificial pollution, test circuit steady state current ratings of 1 A to 5 A, or higher, may be necessary. Refer to 12.3 for additional guidance on power supply requirements when performing alternating voltage artificial contamination tests.

6.2.2.2 The high-voltage series resonant circuit

The high-voltage series resonant circuit consists essentially of an inductor in series with a capacitive test object. Alternatively, it may consist of a capacitor in series with an inductive test object. By varying circuit parameters or the supply frequency, the circuit can be tuned to achieve a voltage across the test object considerably greater than that of the source and with a substantially sinusoidal shape. Controlled high-voltage series resonant circuits do not produce overvoltages following disruptive discharges since they "de-tune" whenever the load impedance changes.

For dry tests using series resonant circuits, additional preload capacitance may be necessary to maintain the test voltage in the presence of corona from the high-voltage connections.

The series resonant circuit is useful when testing objects in which the resistive or leakage currents are small in comparison with the capacitive currents. The circuit may be unsuitable for testing external insulation under contaminated conditions. Series resonant circuits may be suitable for wet tests using sufficient preload capacitance.

6.2.2.3 The high-voltage parallel resonant circuit

The parallel resonant circuit consists essentially of a capacitive test object or load in parallel with a fixed or variable inductance and a high-voltage source. By varying circuit parameters or the supply frequency, the circuit can be tuned, resulting in a considerable reduction in the current drawn from the mains supply. Unlike the series resonant circuit, parallel resonant circuits perform like transformer circuits following disruptive discharges and overvoltages may occur.

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6.3 Measuring system requirements for approved measuring systems

6.3.1 Measurement of the test voltage

6.3.1.1 Measurement with approved devices

The measurement of the peak value, the rms value, the deviation from a sinusoid, and any transient drop in the test voltage shall be made with devices in compliance with the required procedures described in 6.5. Attention is drawn to the required characteristics of devices used for measuring transient voltage drops.

6.3.1.2 The sphere gap as an approved measuring device

A sphere gap with dimensions as given in Clause 14, and used in accordance with this clause, is an approved measuring system for alternating voltage.

6.3.2 Quantities to be measured, and uncertainties required

6.3.2.1 Peak or rms value of the test voltage

The peak or rms value of the test voltage shall be measured with an overall uncertainty of not more than ± 3%.

This requirement will be met if the measuring system meets the performance requirements described in 6.5, and the specified performance tests show that the scale factor of the measuring system is stable and known with an overall uncertainty of not more than ± 3%.

The response time of the measurement system should be sufficient to track the rate of rise of the test voltage. Systems used to make measurements in wet tests or pollution tests must be capable of measuring the stability of the test voltage.

6.3.2.2 Harmonics

The frequency response of an approved measurement system is adequate if the scale factor for each harmonic frequency to the 7^{th} harmonic is within 10% of the scale factor determined in the most recent performance test.

Frequency response requirements are waived for measuring systems used on series resonant systems or transformer systems if it can be demonstrated that the ratio of peak to rms test voltage value equals $\sqrt{2}$ within ± 1% for all expected operating conditions.

6.3.2.3 Transient voltage drops due to external nondisruptive discharges (when required)

Non-disruptive discharges internal to the test object are normally of insufficient charge magnitude to affect the test voltage. External non-disruptive discharges can be of sufficient charge magnitude (i.e., streamers) to affect the test voltage. These conditions are often present during tests at very high voltages and in circuits with large physical dimensions. In general, the test voltage disturbances caused by these discharges

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may be captured by a measurement system with a high bandwidth, as specified by the relevant apparatus standard.

6.4 Test procedures

6.4.1 Withstand voltage tests

The voltage shall be applied to the test object starting at a value sufficiently low to prevent any effect of overvoltages due to switching transients. It should be raised sufficiently slowly to permit accurate reading of the measuring instrument, but not so slowly as to cause unnecessarily prolonged stress on the test object at the test voltage. These requirements are met in general if the rate of rise above 75% of the estimated final test voltage is about 2% of the test voltage per second. The test voltage should be maintained for the specified time and then reduced, but it should not be suddenly interrupted as this may generate switching transients that could cause damage or erratic test results. Unless otherwise specified by a relevant apparatus standard, the duration of a withstand test shall be 60 seconds. The requirements of the test are generally satisfied if no disruptive discharge occurs on the test object.

NOTE—When using series resonant systems, care should be taken when tuning to maintain a controlled rate of voltage rise.

6.4.2 Disruptive discharge voltage tests

The voltage shall be applied and raised as described in 6.4.1 or as specified by the relevant apparatus standard until a disruptive discharge occurs on the test object. The value of the test voltage reached just prior to the disruptive discharge shall be recorded.

The relevant apparatus standard shall specify the number of voltage applications, and the procedure for evaluation of the test results.

The disruptive discharge voltage of a test object is subject to statistical variations. Some guidance on methods for determining voltages giving a specified disruptive discharge probability is presented in Clause 15.

6.4.3 Assured disruptive discharge voltage tests

The voltage shall be applied and raised as described in 6.4.1 or as specified by the relevant apparatus standard until a disruptive discharge occurs on the test object. The value of the test voltage reached just prior to the disruptive discharge shall be recorded.

The relevant apparatus standard shall specify the number of voltage applications.

The requirements of the test are generally satisfied if this voltage does not exceed the assured disruptive discharge voltage on a specified number of voltage applications.

6.4.4 Capacitance and dielectric loss measurements

6.4.4.1 General

Insulating materials are generally used either to:

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a) Support components of a system physically and, at the same time, insulate them electrically from each other and from ground; or

b) Act as a dielectric in a capacitor system.

Practical insulating materials are imperfect and exhibit losses when subjected to high-voltage stresses. Knowledge of these losses is of importance to the designer and operator of power apparatus in order to avoid excessive energy dissipation, which could cause thermal instability leading to breakdown as a result of dielectric heating effects. Loss measurements at regular intervals during the life of power apparatus are also used as a diagnostic tool to detect insulation degradation due to aging, moisture ingress, or other phenomena.

6.4.4.2 Equivalent circuits

Any insulation structure is highly complex and, for numerical and experimental evaluation of dielectric losses, simplified equivalent circuits are normally used. Two equivalent circuits that are in common use are:

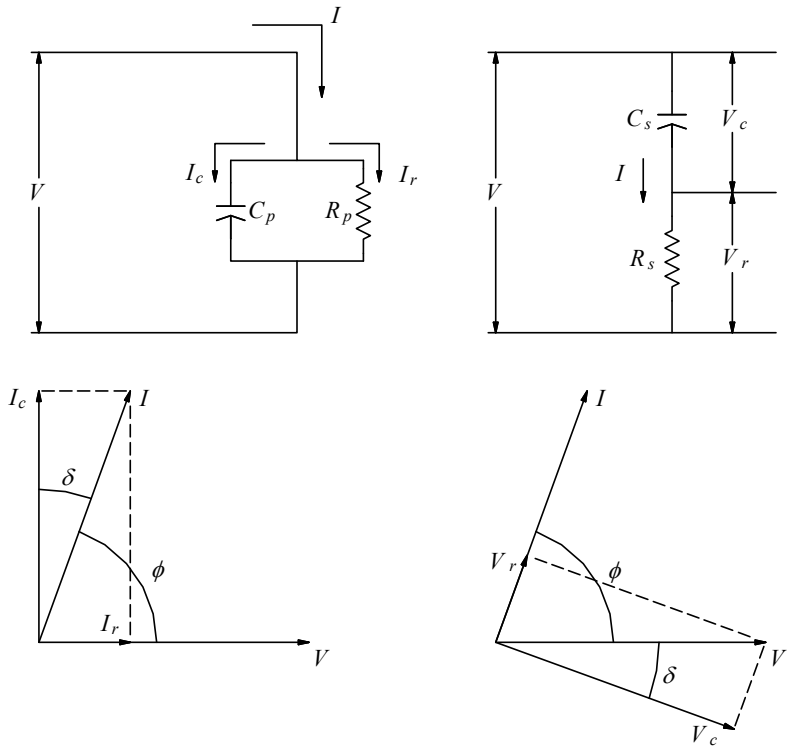
a) The parallel equivalent circuit.

b) The series equivalent circuit.

These equivalent circuits are shown in Figure 3, together with their respective phasor diagrams. The equivalent circuits are simply a convenient arrangement of circuit elements that may be used to calculate certain quantities (such as power factor) from the measurement of others (e.g., voltage, current, and power) in order to draw conclusions regarding the quality of the complete insulation system.

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Parallel Equivalent Circuit

Series Equivalent Circuit

I_c is the current through the capacitor C_p
I_r is the current through the resistor R_p
C_p is the capacitance of the parallel circuit
R_p is the resistance of the parallel circuit
C_s is the capacitance of the series circuit
V_c is the voltage across the capacitor C_s
V_r is the voltage across the resistor R_s
R_s is the resistance of the series circuit

Figure 3—Equivalent circuits for dielectric loss measurement

It should be noted that the values of equivalent resistance (R) and capacitance (C), of the complete insulation system, which are obtained by measurement, apply only to the particular conditions of voltage, frequency, temperature, etc., that exist during the measurement. If any of the above quantities are changed, different values of R and C may be obtained.

The effects of temperature on power factor are well known for many different types of power apparatus. Measurements of power factor at a reference temperature may be obtained from measurements at another temperature by the application of temperature correction factors.

Some commercially available instruments perform measurements at frequencies other than power frequencies. In contrast to temperature correction factors, frequency correction factors have not been established. Consequently, caution is advised when interpreting measurements made at other frequencies since they cannot necessarily be correlated to equivalent values at power frequencies.

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6.4.4.3 Evaluation of dielectric loss parameters

Quantities related to dielectric losses are obtained from the following equations for the respective circuits of Figure 3 as follows:

a) Parallel equivalent circuit

$$\text{Dissipation factor or } \tan\delta = \frac{I_r}{I_c} = \frac{1}{\omega R_p C_p} \tag{15}$$

$$\text{Power factor (or cosine } \phi) = \frac{I_r}{I} = \frac{1}{\sqrt{1+\omega^2 R_p^2 C_p^2}} \tag{16}$$

b) Series equivalent circuit

$$\text{Dissipation factor (or } \tan\delta) = \frac{V_r}{V_c} = \omega R_s C_s \tag{17}$$

$$\text{Power factor (or cosine } \phi) = \frac{V_r}{V} = \frac{\omega R_s C_s}{\sqrt{1+\omega^2 R_s^2 C_s^2}} \tag{18}$$

NOTE—For both parallel and series equivalent circuits, when δ (in radians) is small (< 0.2 rad), tangent δ approximates δ, and the dissipation factor approximates the power factor.

The quantities C_s, C_p, R_p, and R_s are related by means of the following equations:

$$C_p = \frac{C_s}{1+(\tan\delta)^2} = \frac{C_s}{1+(\omega R_s C_s)^2} \tag{19}$$

where

$$C_s = C_p\left[1+(\tan\delta)^2\right] = C_p\left[1+\frac{1}{(\omega R_p C_p)^2}\right] \tag{20}$$

$$R_p = R_s\left[1+\frac{1}{(\tan\delta)^2}\right] = R_s\left[1+\frac{1}{(\omega R_s C_s)^2}\right] \tag{21}$$

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$$R_s = \frac{R_p}{1+\frac{1}{(\tan\delta)^2}} = \frac{R_p}{1+(\omega R_p C_p)^2} \tag{22}$$

6.4.4.4 Measurement methods

Dielectric measurements at power frequency are generally made by means of bridge measurement techniques. The two basic types of bridges that are commonly used are the Schering bridge and the transformer ratio-arm bridge. Their principles are described in the following paragraphs; however, a large number of generic variations are commercially available, and their corresponding balance equations may be different from those presented here. In the following paragraphs, the parallel equivalent circuit is assumed.

6.4.4.4.1 Schering bridge

The basic circuit is shown in Figure 4.

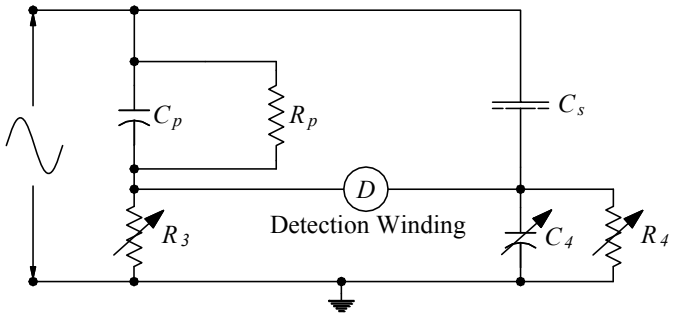


Figure 4—Measurement method – Schering bridge basic circuit

At balance, the values of R_p and C_p are given by:

$$R_p = R_3\left(\frac{C_4}{C_s}\right) \tag{23}$$

$$C_p = C_s\left(\frac{R_4}{R_3}\right) \tag{24}$$

where

C_p, R_p present the parallel equivalent circuit elements of the insulation system under test

R_3, R_4 are variable resistors in the bridge

C_4 is a variable capacitor in the bridge

C_s is the reference capacitor

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For small values of δ, the dissipation factor and the power factor are approximately equal and are calculated from:

$$\delta = \frac{1}{\omega R_p C_p} \tag{25}$$

6.4.4.4.2 Transformer ratio arm bridge

A typical circuit for this type of bridge is shown in Figure 5. A special transformer having two ratio windings, N_1 and N_2, and a detection winding, D, is used. Adjustment is accomplished by varying the number of turns N_1 until the ampere-turn balance is obtained. The balance condition results in zero magnetic flux in the core. The null indicator connected to the detection winding responds to the net flux in the core and thus indicates the state of balance.

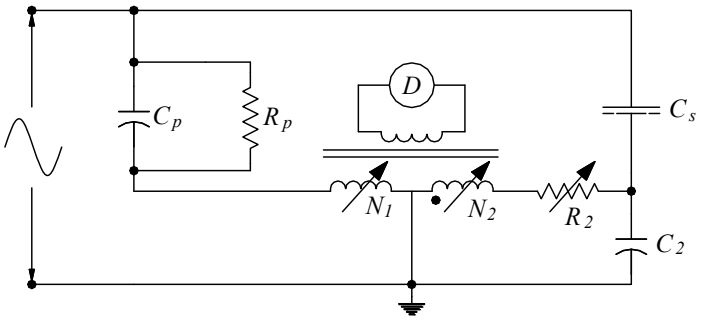


Figure 5—Measurement Method – transformer ratio arm bridge basic circuit

At balance, the values of R_p and C_p are given by:

$$R_p = \frac{N_1}{N_2}\left(\frac{1}{\omega^2 R_2 C_2 C_s}\right) \tag{26}$$

$$C_p = \frac{N_1}{N_2}\left(\frac{C_s}{1+\omega^2 R_2^2 C_2^2}\right) \tag{27}$$

where

C_p, R_p present the parallel equivalent circuit elements of the insulation system under test

R_2 is a variable resistor in the bridge

C_2 is a capacitor in the bridge

C_s is the reference capacitor

As in the case of the Schering Bridge for small values of δ:

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$$\delta = \frac{1}{\omega R_p C_p} \tag{28}$$

or

$$\delta = \omega R_2 C_2 \tag{29}$$

6.4.4.5 General requirements relating to the measurement system and the test object

The reference capacitor (C_s) is usually a carefully shielded, high-voltage, low-loss capacitor insulated with compressed gas. For practical circuits, the capacitor may be considered to be of constant capacitance and loss-free.

The presence of moisture in the test object or in neighboring objects has a significant effect on the dissipated energy and power factor. Therefore, clearances to neighboring semiconducting surfaces such as concrete walls, wooden structures, etc., should not be less than 1.5 times the length of the test object irrespective of the voltage required for the measurement. In addition, measurements should not be made at temperatures below 0 °C because moisture can only exist as ice under such circumstances, resulting in substantially lower levels of dissipated energy and power factor.

When measurements are performed on objects that are highly resistive, δ will be almost 90° and ϕ will be almost 0°. Therefore, it is essential to use a bridge that measures power factor rather than tan δ because the maximum power factor can never exceed 1, whereas the maximum value of tan δ will be infinite and, as such, cannot be realized in any practical bridge.

The low-voltage end of the test object is normally insulated from ground and connected to the measuring bridge. For test objects with one side grounded, the bridge circuits can still be used; however, stray capacitances and dielectric losses of the test voltage source and high-voltage connections will be measured in addition to those of the test object. Therefore, two series of measurements are normally performed. In the first, the test object is disconnected from the high-voltage supply. The bridge-ground connection is transferred to the input terminal that would normally be connected to the low-voltage end of the test object, and the capacitance (C_1) and dissipation factor (tan δ_1) are measured. The test object is then connected to the high-voltage supply and the new capacitance (C_2) and dissipation factor (tan δ_2) are measured. The capacitance of the test object (C_x) is determined from:

$$C_x = C_2 - C_1 \tag{30}$$

and

$$\tan\delta = \frac{C_2 \tan\delta_2 - C_1 \tan\delta_1}{C_2 - C_1} \tag{31}$$

For measurements in the field, test circuits are used that have specially shielded test transformers, high-voltage leads, measuring cables, and associated measuring circuits. Such test circuits usually operate at voltages up to approximately 10 kV and can be used for measurements on grounded or ungrounded test objects.

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6.5 Type tests, acceptance tests, performance tests, and performance checks for alternating voltage measuring systems

The following tests are described to characterize the performance of an alternating voltage measuring system. See Clause 5 for descriptions of the measurement system classifications, record of performance requirements, and explanation of terminology.

6.5.1 Type tests (verification of a new design)

The following type tests shall be performed on approved measuring systems by the manufacturer as verification of the design. It is not required that the results of these tests be kept in the owner's record of performance; however, the manufacturer of the measuring system shall maintain the test results, and shall make them available to the user of the measuring system upon mutual agreement.

The type tests for alternating voltage measuring systems include:

a) Verification of the operating temperature range (complete measuring system, major subassemblies, or individual components).
b) Frequency response (see 6.3.2.2).
c) Verification of duty cycle (complete measuring system, or major subassemblies).
d) Proximity effects.
e) Acceptance tests (see 6.5.2).

6.5.2 Acceptance tests (new systems, or after major system repair or alteration)

An acceptance test shall be performed on all approved measuring systems, with the results documented in the record of performance, in accordance with the general requirements stated in Clause 5. An acceptance test is required as a one-time test on new measuring systems, or as a follow-up test that shall be made after any major measuring system repairs or alterations.

The acceptance tests for alternating voltage measuring systems include:

a) Determination of the measuring system short-term stability.
b) Withstand voltage test.
c) Performance tests (see 6.5.3).

The test report of the system manufacturer may serve as a valid acceptance test result for new measuring systems.

6.5.3 Performance tests (annually or according to record of performance requirement)

A performance test shall be performed either on an annual basis, or at intervals specified in the record of performance for the measuring system.

The performance tests of alternating voltage measuring systems include:

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a) Determine or verify the measuring system scale factor.

b) Determine or verify the measuring system linearity.

6.5.3.1 Test for scale factor

The scale factor shall be determined or verified by comparison to a reference measuring system with a known scale factor at not less than 20% of the maximum operating voltage of the measuring system, with overall uncertainty consistent with the requirements stated in Clause 5 and traceable to national standards.

6.5.3.2 Test for linearity

The linearity shall be determined or verified by one of the following methods:

a) Comparison to an approved measuring system with overall uncertainty consistent with the requirements stated in Clause 5.

b) Comparison with the current from a plate electrode. Alternatively, the plate capacitor can be connected to a low-voltage plate capacitor to form a voltage divider.

c) Comparison with the output from an electric field strength meter.

When a sphere gap is used for a linearity test, comparisons should be performed using the procedures and dimensions as given in Clause 14.

To qualify as an approved measuring system, the ratio of the measured voltage to the corresponding input voltage must not deviate by more than 1% from the calculated mean value of five ratios, measured at five approximately equally spaced voltages ranging from 10% to 100% of the maximum operating voltage of the measuring system.

6.5.4 Performance checks (At regular intervals)

A performance check of the measuring system may be performed by the user at any time between performance tests when it is deemed necessary to verify the correct function and approximate accuracy of an approved measuring system for a specific test.

The scale factor check for purposes of a performance check may be accomplished at any voltage up to 100% of the rated voltage of the measuring system by direct comparison to another approved measuring system.

If the scale factor measured during the performance check deviates by more than 3% from the scale factor determined in the last performance test, further investigation is required to determine the cause.

NOTE—Use of low-voltage techniques to check the scale factor is allowed.

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6.6 Additional information on alternating voltage test and measurement techniques

6.6.1 Measuring systems for alternating voltage

The following systems will measure the peak, the rms, or the mean value of an alternating voltage according to the type of instrument and arrangement used. Measurement of the rectified capacitive current (see 6.6.1.2) determines the peak-to-peak amplitude, and the electrostatic voltmeter (see 6.6.1.3) measures the rms value.

6.6.1.1 Electronic instrument used with a voltage divider or a suitable potential (voltage) transformer

A voltmeter or oscilloscope specifically designed to electronically measure peak, rms, or average voltage is connected across the low-voltage arm of the divider through a measuring cable. The input impedance of the low-voltage measuring circuit and the capacitance of the measuring cable should be taken into account in the determination of the measuring system scale factor.

6.6.1.2 Capacitor used with a rectifying device

This circuit is typically used when the test voltage is to be displayed on a dc ammeter. A capacitor in series with a full-wave rectifier is connected to the low-voltage arm of the measuring system. The circuit indicates a voltage proportional to the peak value developed across the low-voltage arm according to:

$$V_p = \frac{I_r}{4Cf} \tag{32}$$

where

C is the capacitance of the series capacitor

f is the frequency of the test voltage

NOTE—This circuit may not be suitable for measuring voltages with significant harmonic distortion.

6.6.1.3 High-voltage electrostatic voltmeter

This device is described in 7.6.1.3 for use with direct voltages. It can also be used for directly measuring the rms value of alternating voltages over a wide range of frequencies without a separate voltage divider. The advantage of the electrostatic voltmeter is very high input impedance that will not load the test voltage source.

6.6.2 Instrument for measuring the amplitude of harmonics

A harmonic analyzer is a digital instrument that separates the magnitude of the individual voltage harmonics directly and accurately. Harmonic analyzers should be used with voltage dividers or potential transformers of sufficient bandwidth to measure the highest frequency anticipated. Normally, harmonics up to the 7^{th} are measured.

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6.6.3 Ratio measurements

When the high-voltage arm of a capacitive divider consists of a large number of series-connected capacitor elements, the divider ratio will be affected by stray capacitance from the high-voltage capacitor column to ground and to high-voltage leads, etc. These proximity effects will change each time the physical arrangement of the test circuit, including the measuring system, is changed. Therefore, it may be necessary to measure the ratio of the divider each time the test circuit arrangement is changed, unless experience in a particular laboratory indicates that variations in ratio due to stray capacitance effects are within acceptable limits. The equivalent capacitance (including effects of stray capacitances) of the high-voltage arm can be measured by means of a high-voltage capacitance bridge.

The capacitance of the low-voltage arm can also be measured by means of a capacitance bridge and, although it is usually unaffected by proximity effects, this capacitance shall also include the capacitance of the measuring cable.

When the high-voltage arm of a capacitive divider consists of a high-voltage compressed-gas standard capacitor of a totally shielded type construction, such a divider will be unaffected by proximity effects. In addition, the accuracy and stability of this type of capacitor is at least one order of magnitude higher than the requirements specified in this standard. Therefore, traceable nameplate values may be used, provided that their capacitance is measured at least once (and after any repairs or modifications). As in the previous case, the capacitance of the measuring cable shall be included when measuring the total capacitance of the low-voltage arm.

Potential transformers, reference capacitive dividers, or compressed-gas standard capacitors may be used as reference measuring systems. However, if the test voltage waveform contains harmonics, the measurement of these harmonics by a potential transformer may be incorrect.

6.6.4 Linearity

The linearity of an alternating voltage divider may be affected by corona from intermediate electrodes on the high-voltage arm or by leakage currents flowing over external surfaces, particularly if the surfaces become wet because of condensation or outdoor operation during rain. The nonlinearity may also be due to the inherent nonlinearity of the capacitor elements that were used in the construction of the divider.

A simple method to check linearity for sources with low harmonic content uses a flat electrode insulated from ground in a fixed proximity to the high-voltage electrode of the test source. The flat electrode is connected to ground through an alternating current meter. If the high-voltage electrodes are corona-free, the current measured in such a way will be proportional to the output voltage of the test source. Since the flat electrode is normally mounted remotely from the control room, protective devices should be connected from the electrode to ground to protect instrumentation from damage. Care should be taken to place the electrode at a safe distance to prevent flashover.

Electric fields in the proximity of test sources are directly proportional to the output voltages of those sources in the absence of corona. Therefore, techniques based on electric field strength measurements may also be used as comparative systems when checking the linearity of alternating voltage dividers. The electric field strength meters may be positioned on either the high-voltage electrode of the test source or at ground potential on nearby walls or ceiling. The ground-reference meter is a simple type of instrument that can be used for this application. It can also be used on energized flat surfaces provided that the reference potential of the detector is the same as that of the energized surface. Provision has to be made for remote viewing of the analog or digital display (e.g., fiber-optic link or viewing the detector display from a distance). For this application, only a signal proportional to the electric field strength is sought, and hence the absolute value of the electric field strength is not required, thereby eliminating the need to calibrate the electric field strength meter.

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For linearity verification of voltage dividers, electric field strength measuring instruments based on charge measurements are preferable to those that measure current when a test transformer is used as the voltage source because of the possible presence of harmonics on the voltage waveform. Instruments that measure current are acceptable for series-resonant systems because the total harmonic content of such systems is typically less than 0.5%.

6.6.5 Possible sources of error in alternating voltage measurement

Due to the high impedances of some voltage dividers and series impedance elements, the effects of corona or stray capacitances (or both) may result in serious errors. Such errors can often be minimized by the use of suitably dimensioned high-voltage electrodes and guard circuits. To reduce such effects on capacitive dividers, it is recommended that, when the capacitor is not effectively shielded, the overall series capacitance in picofarads be at least 50 to 100 times the overall height of the divider in meters, depending on the circuit loading.

Errors may also be caused by capacitors that have significant voltage or temperature instability and by instruments that are subject to drift.

Electrostatic and generating voltmeters may develop errors due to field distortion arising from electrostatic charges on the surfaces of insulating materials.

When a high-voltage series capacitor is used for voltage measurement, special protection of the measuring instrument is necessary during disruptive discharge tests. Disruptive discharge of a test object connected in parallel with such measuring systems results in the application of fast-rising high-voltage surges to the instruments, which therefore require suitable protection.

6.6.6 Determination of the frequency response of a measuring system

To determine the frequency response of a measuring system, a sinusoidal voltage is applied to its input terminals. The ratio of the output to the input amplitudes is recorded as a function of frequency. The range of frequencies should extend from the fundamental to at least the highest harmonic of interest present in the voltage to be measured. The measurements are usually made at a low value of input voltage, and may be performed separately on the divider and the measuring device.

In an alternative technique for the divider only, a periodic square wave is applied and the frequency spectra of the input and output signals determined by means of a harmonic analyzer. The period of the square wave should be the same as the period of the fundamental frequency to be measured. Some harmonic analyzers utilize the Fast Fourier Transform (FFT) method to determine the harmonic amplitudes. In such a case, care has to be taken to process one complete period of the waveform being investigated.

Another technique for the divider only is the transfer function [H(f)] technique. This technique can also be used to determine the amplitude-frequency and phase-frequency response of devices such as potential transformers, power transformers, bushing current transformers, etc. The test method consists of applying a voltage or current impulse to the input of the device. Input and output waveforms are digitally recorded. Then H(f) is computed as the FFT of the output waveform divided by the FFT of the input waveform. The pulse waveforms shall be recorded for their entire duration or properly truncated by appropriate software. The transfer function technique can also be used to interpret transformer impulse and transformer short circuit test results.

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7. Tests and measurements with direct voltage

7.1 Terms used to characterize direct voltage tests and measurements

value of the test voltage: The arithmetic mean value of the test voltage.

ripple: The periodic deviation from the arithmetic mean value of the test voltage.

ripple amplitude: Half the difference between the maximum and minimum values of the test voltage.

NOTE—In practical cases where the ripple voltage may be approximated by a sinusoid, the measured true rms value of the ripple voltage multiplied by a factor of 1.4 is also acceptable for the determination of the ripple amplitude.

ripple factor: The ratio of the ripple amplitude to the value of test voltage.

7.2 Source requirements

7.2.1 Requirements for the test voltage

7.2.1.1 General requirements

The test voltage applied to the test object shall be a direct voltage with a ripple factor of no more than 3%, unless specified by a relevant apparatus standard. The ripple factor may be affected by the presence of the test object and by test conditions, especially during contamination tests.

NOTE—Ripple amplitude is directly related to resistive load currents. Dielectric testing where heavy streamers are present may cause excessive ripple. Wet testing and contamination testing by their very nature require sources suitable for supplying high resistive currents. Refer to Clause 11 and Clause 12 for general information relating to wet tests and contamination tests.

7.2.1.2 Test voltage tolerance

If not otherwise specified by the relevant apparatus standard, the measured value of the test voltage shall be maintained within ± 3% of the specified level for tests of 5 minutes or less.

The voltage source, including its storage capacitance, shall be adequate to supply any transient currents with a voltage drop of less than 10%. If transient currents are encountered during a test, the voltage measuring system must be adequate to measure the resulting transient voltages. Refer to 7.3.2.3 for special measuring system response requirements when it is necessary to measure transient voltages.

The maximum allowed transient voltage drop/overshoot when performing artificial contamination tests is specified in Clause 12.

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7.3 Measuring system requirements for approved measuring systems

7.3.1 Measurement of the test voltage

7.3.1.1 Measurement with approved devices

The measurement of the arithmetic mean value, the maximum value, the ripple factor, and any transient drop in the test voltage shall be made with devices in compliance with the required procedures described in 7.5. Attention is drawn to the required characteristics of devices used for measuring ripple factor or transient voltages.

7.3.1.2 The rod gap as an approved measuring device

A rod gap used in accordance with the dimensions as given in Clause 14, and used in accordance with this clause, is an approved measuring system for direct voltage. These gaps may be used with voltages above 135 kV and less than 1335 kV.

7.3.2 Quantities to be measured, and uncertainties required

7.3.2.1 Arithmetic mean value of the test voltage

The arithmetic mean value of the test voltage shall be measured with an overall uncertainty of not more than ± 3%.

This requirement will be met if the measuring system meets the performance requirements described in 7.5, and the specified performance tests show that the scale factor of the measuring system is stable and known with an overall uncertainty of not more than ± 3%.

The response time of the measurement system should be sufficient to track the rate of rise of the test voltage.

7.3.2.2 Ripple amplitude (when required)

NOTE—Ripple amplitude measurements are recommended when the resistive test load currents are outside of the load range for which ripple amplitude is known or specified for the test source.

When it is necessary to determine the ripple factor, the peak to peak ripple amplitude shall be measured with an overall uncertainty of not more than ± 10% of the measured ripple amplitude, or an overall uncertainty of not more than ± 1% of the arithmetic mean value of the test voltage, whichever is larger.

This requirement will be met if the measuring system, in addition to meeting the performance requirements described in 7.5, is demonstrated to be in compliance with the following additional requirements:

a) For parallel resistive/capacitive dividers, the nominal value of the RC time constants of the high-voltage and low-voltage arms shall be adjusted to ensure an adequate frequency response.

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b) The frequency response of the system used for measuring ripple voltage is adequate if the scale factor is known to within 10% for frequencies from the fundamental of the ripple frequency up to five times this frequency. For practical reasons, a frequency response check is allowed to be made by applying a low alternating voltage to the divider, at the fundamental ripple frequency, and measuring the output voltage developed across the low-voltage arm impedance to determine the scale factor. For high ratio dividers, the alternating voltage measuring equipment used shall have sufficient accuracy at the voltage levels being measured. Alternative methods to determine the frequency response, such as step response and/or transfer function measurements, may also be used.

c) High ohmic value resistive dividers without parallel-connected capacitance may be inadequate to measure the ripple on the output voltage. In addition, for direct voltage test systems that require automatic voltage control (for example, systems for pollution testing or fast charging systems for capacitive loads), the control and measuring systems shall have a rapid transient response; conventional, high ohmic value resistive dividers will not normally have a sufficiently rapid response. For such cases, a measuring system comprising a compensated parallel connected resistance/capacitance network will provide an adequate high frequency response that will meet the high frequency requirements.

7.3.2.3 Transient voltage drops due to external non-disruptive discharges (when required)

Non-disruptive discharges internal to the test object are normally of insufficient charge magnitude to affect the test voltage. External non-disruptive discharges can be of sufficient charge magnitude to affect the test voltage (i.e., streamers). These conditions are often present during tests at very high voltages and in circuits with large physical dimensions. In general, the test voltage disturbances caused by these discharges may be captured by a measurement system with a high bandwidth, as specified by the relevant apparatus standard. Measurement of voltage drops caused by external non-disruptive discharges is normally performed using compensated parallel RC or mixed RCR type dividers.

7.4 Test procedures

7.4.1 Withstand voltage tests

The voltage shall be applied to the test object starting at a value sufficiently low to prevent any effect of overvoltage due to switching transients. It should be raised sufficiently slowly to permit accurate reading of the instruments, but not so slowly as to cause unnecessarily prolonged stress on the test object at the test voltage. Generally, these requirements are met if the rate of rise above 75% of the withstand voltage is about 2% of the withstand voltage per second. The voltage shall be maintained for the specified time and then reduced by discharging the circuit capacitance, including that of the test object, through a suitable resistor. Unless otherwise specified by a relevant apparatus standard, the duration of a withstand test shall be 60 seconds. The test requirements are generally satisfied if no disruptive discharge occurs on the test object.

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The polarity of the voltage or the order in which voltages of each polarity are applied (and any deviation required from the above) shall be specified by the relevant apparatus standard.

7.4.2 Disruptive discharge voltage tests

The voltage shall be applied and raised as described in 7.4.1, or as specified by the relevant apparatus standard until a disruptive discharge occurs on the test object. The value of the test voltage reached just prior to the disruptive discharge shall be recorded.

The relevant apparatus standard shall specify the number of voltage applications, and the procedure for evaluation of the test results.

The disruptive discharge voltage of a test object is subject to statistical variations. Some guidance on methods for determining voltages giving a specified disruptive discharge probability is presented in Clause 15.

7.4.3 Assured disruptive discharge voltage tests

The voltage shall be applied and raised as described in 7.4.1, or as specified by the relevant apparatus standard until a disruptive discharge occurs on the test object. The value of the test voltage reached just prior to the disruptive discharge shall be recorded.

The relevant apparatus standard shall specify the number of voltage applications.

The requirements of the test are generally satisfied if this voltage does not exceed the assured disruptive discharge voltage on a specified number of voltage applications.

7.5 Type tests, acceptance tests, performance tests, and performance checks for direct voltage measuring systems

The following tests are described to characterize the performance of a direct voltage measuring system. See Clause 5 for descriptions of the test protocol, measurement system classifications, record of performance requirements, and explanation of terminology.

7.5.1 Type tests (Verification of a new design)

The following type tests shall be performed on approved measuring systems by the manufacturer as verification of the design. It is not required that the results of these tests be kept in the owner's record of performance; however, the manufacturer of the measuring system shall maintain the test results, and shall make them available to the user of the measuring system upon mutual agreement.

The type tests for direct voltage measuring systems include:

a) Verification of the operating temperature range (on the complete measuring system, on major subassemblies, or on individual components).
b) Transient response if required (complete measuring system only).
c) Verification of duty cycle (complete measuring system, or major subassemblies).
d) Acceptance tests (see 7.5.2).

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7.5.2 Acceptance tests (New systems, or after major system repair or alteration)

An acceptance test shall be performed on all approved measuring systems, with the results documented in the record of performance, in accordance with the general requirements stated in Clause 5. An acceptance test is required as a one-time test on new measuring systems, or as a follow-up test that shall be made after any major measuring system repairs or alterations.

The acceptance tests for direct voltage measuring systems include:

a) Determination of the measuring system short-term stability.

b) Withstand voltage test.

c) Performance tests (see 7.5.3).

The measuring system manufacturer's test report may serve as a valid acceptance test result for new measuring systems.

7.5.3 Performance tests (annually or according to record of performance requirement)

A performance test shall be performed either on an annual basis, or at intervals specified in the record of performance for the measuring system.

The performance tests of direct voltage measuring systems include:

a) Determine or verify the measuring system scale factor.

b) Determine or verify the measuring system linearity.

7.5.3.1 Test for scale factor

The scale factor shall be determined or verified by comparison to a reference measuring system with a known scale factor at not less than 20% of the maximum operating voltage of the measuring system, with overall uncertainty consistent with the requirements stated in Clause 5 and traceable to national standards.

7.5.3.2 Test for linearity

The linearity shall be determined or verified by one of the following alternatives based on the availability of measuring equipment. Linearity determination by comparison to another approved measuring system is the preferred method.

For systems that exhibit predictable nonlinearity, calibration curves that have been established through direct comparison with a reference measuring system may be referenced when demonstrating compliance with the requirements of a performance test. When referenced, these curves must be included in the record of performance for the measuring system, along with any restrictions or limitations associated with their use.

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7.5.3.2.1 Linearity determination by comparison to another approved measuring system

To qualify as an approved measuring system, the ratio of the measured voltage to the corresponding input voltage must not deviate by more than 1% from the calculated mean value of five ratios, measured at five approximately equally spaced voltages ranging from 10% to 100% of the operating range of the measuring system.

When a rod gap is used for linearity determination, comparisons should be performed using the procedures and dimensions as given in Clause 14 and used in accordance with 7.3.1.2.

7.5.3.2.2 Linearity determination by comparison to rectifier input voltage

In the absence of another direct voltage approved measuring system, for direct voltage sources based on half-wave, full-wave, or cascade rectifier circuits, the linearity determination for the purposes of the performance test may be accomplished by comparison of the peak value of the output alternating voltage of the energizing transformer to the output direct voltage of the rectifier. The output alternating voltage of the energizing transformer is proportional to the output direct voltage of the rectifier within the degree of uncertainty required by this standard. The alternating voltage measuring system used in this comparison shall meet the requirements for an approved measuring system, as described in Clause 5 and Clause 6 of this standard.

7.5.3.2.3 Linearity determination by intermediate direct voltage measurement within the rectifier stack

A rectifier stack can be characterized as intermediate points within a Cockroft-Walton cascade voltage multiplier (capacitively coupled) or a magnetically coupled cascade of voltage doublers. In all cases, the high-voltage assembly must be discharge-free and free from non-linear stray leakage currents that will affect the voltage output. As an alternative to comparison to rectifier input voltage, linearity may be verified by making a direct voltage measurement using a second approved direct voltage measuring system connected to an intermediate level in the rectifier stack, at a level of not less than 20% of the total stack. Care should be taken to insure that the intermediate loading of the rectifier stack by the second direct voltage measuring system does not affect the high-voltage distribution within the rectifier stack.

7.5.4 Performance checks (at regular intervals)

A performance check of the measuring system may be performed by the user at any time between performance tests when it is deemed necessary to verify the correct function and approximate accuracy of an approved measuring system for a specific test.

The scale factor check for purposes of a performance check may be accomplished at any voltage up to 100% of the rated voltage of the measuring system by direct comparison with another approved measuring system.

If the scale factor measured during the performance check deviates by more than 3% from the scale factor determined in the last performance test, further investigation is required to determine the cause.

NOTE—Use of low-voltage techniques to check the scale factor is allowed.

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7.6 Additional information on direct voltage test and measurement techniques

7.6.1 Systems for measuring the steady state value of direct voltages

7.6.1.1 Instrument used with a voltage divider

A voltmeter is connected across the low-voltage arm of a resistive voltage divider. The resistance of the voltmeter shall be taken into account when determining the ratio of the divider.

7.6.1.2 Instrument used in series with a high-voltage resistor

A direct current measuring instrument is connected in series with a stable high ohmic value resistor, rated for the maximum test voltage.

7.6.1.3 Electrostatic voltmeter

An electrostatic voltmeter has two electrodes that are connected to the points between which the high voltage is to be measured. The electric field between the electrodes generates a force that is proportional to the rms value of the voltage. By measurement of this force, an indication of the rms value of the high-voltage can be derived. This measuring principle can be used over the range of frequencies from zero up to several megahertz. If the measuring system is not shielded, special attention should be given to errors caused by stray fields and space charges.

7.6.2 Systems for measuring ripple amplitude

7.6.2.1 Oscilloscope or digital recorder used with voltage divider

An oscilloscope or digital recorder is connected to the low-voltage arm of a voltage divider having a suitable frequency response (7.3.2.2). It should be noted that the capacitance of the cable between the divider and the instrument can modify the frequency response and scale factor, and that the ripple measuring system itself can modify the ripple content of the system.

7.6.2.2 Instrument used with filter

Such a device consists, in general, of an instrument connected to the circuit in such a way that the direct voltage component is filtered out. A typical arrangement consists of a high-voltage capacitor in series with a resistor or capacitor across which a voltage-measuring instrument is connected.

7.6.2.3 Instrument measuring the rectified current through a capacitor

A capacitor in series with a full-wave rectifier is connected to the points between which the voltage is to be measured. Providing that:

a) There is only one peak during each half-cycle.

b) The positive and negative half-cycles have the same peak value.

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The average value of the rectified current, I_r, flowing through the capacitor is then related to the ripple amplitude by:

$$V_r = \frac{I_r}{4Cf} \tag{33}$$

where

C is the capacitance of the capacitor

f is the fundamental ripple frequency.

Because the ripple amplitude is defined in terms of half the difference between the maximum and minimum values of the test voltage, the second restriction is met by the same definition.

Similarly, if a half-wave rectifier is used in place of a full-wave and the same restrictions are met, the ripple amplitude is related to the average value of the rectified current by the following expression:

$$V_r = \frac{I_r}{2Cf} \tag{34}$$

7.6.2.4 Measurement using a voltage divider with an rms responding meter

In circuits in which the ripple voltage may be approximated by a sinusoid, the ripple voltage may be measured by using a true rms responding meter connected across the low-voltage arm of a suitable voltage divider. The voltage divider used should comply with the requirements stated in 7.3.2.2.

7.6.3 Measurement of the test current

When measurements of the current through the test object are made, a number of separate current components may be recognized. These differ from each other by several orders of magnitude for the same test object and test voltage. They are:

a) Capacitive charging current, due to the initial application of the test voltage and to any ripple voltage or other fluctuations superimposed on it.

b) The dielectric absorption current, due to slow charge displacements within the insulation and persisting for periods of a few seconds up to several hours.

c) The continuous leakage current, which is the final steady direct current attained at constant applied voltage after the above components have decayed to zero.

d) Partial discharge currents (internal or external). See IEC 60270 (listed in Clause 2).

Measurements of the first three current components necessitate the use of instruments covering a wide range of current magnitudes. It is important to ensure that the instrument, or the measurement of any one component of the current, is not adversely affected by the other components. Information concerning the condition of the insulation during nondestructive tests may be obtained by observing current variations with respect to time.

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The relative magnitude and the importance of each current component depend on the type and the conditions of the test object, the purpose of the test, and the duration of the test. Accordingly, the measurement procedures should be specified by the relevant apparatus standard, especially when a particular component must be distinguished.

7.6.4 Possible sources of error in direct voltage measurement

7.6.4.1 Voltage dividers

A direct voltage divider may exhibit nonlinear characteristics for a variety of reasons. For example, the resistors used in the construction may be nonlinear with voltage or temperature; leakage current along the outside of the housing of the high-voltage arm may add to the total current and thereby cause a significant measuring error, particularly during humid conditions. In the case of air-insulated dividers, leakage currents across individual resistor surfaces or resistor supports can cause errors similar to those mentioned above for external surface leakage currents.

Corona from intermediate electrodes may cause a nonlinear characteristic and, if the low-voltage arm is unshielded, additional errors may arise due to the effect of corona currents that flow through the surrounding air and that tend to concentrate in areas of high electric field strength. Surface leakage and corona currents can usually be intercepted by means of suitable guard and shield electrodes, respectively.

The linearity may be demonstrated by comparison against a rod gap as described in 7.5.3.2.1, and in accordance with 7.3.1.2. Alternatively, for dividers of modular construction, the linearity of each module may be demonstrated by comparing it up to its rated voltage while connected in parallel with two or more similar, series-connected modules to reduce the stress on each module.

7.6.4.2 Electrostatic voltmeters

Electrostatic voltmeters may develop errors due to field distortion arising from electrostatic charges on the surface of insulating materials or in space.

7.6.5 Testing of alternating voltage apparatus with direct voltage

It is noted that testing of some types of alternating voltage apparatus with direct voltage may cause damage to the insulation, or may produce results inconsistent with test results on the same apparatus made with alternating voltage. The voltage distribution in any high-voltage insulation system is determined by the combined effects of material resistivity (resistive grading effects) and permittivity (capacitive grading effects). Tests made with direct voltage on alternating current apparatus do not generally simulate in service stresses based on the lack of capacitive grading influences. The capacitive grading is usually the dominant influence in determining voltage distribution within an alternating voltage insulation system. Tests made with direct voltage on alternating current apparatus should therefore be approved by the relevant apparatus committee.

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8. Tests and measurements with impulse voltage

8.1 Terms used to characterize impulse voltage tests and measurements

lightning impulse: An impulse with a front time up to 20 μs.

full lightning impulse: A lightning impulse that is not interrupted by a disruptive discharge (see Figure 6).

NOTE—This waveshape can be represented by a double exponential.

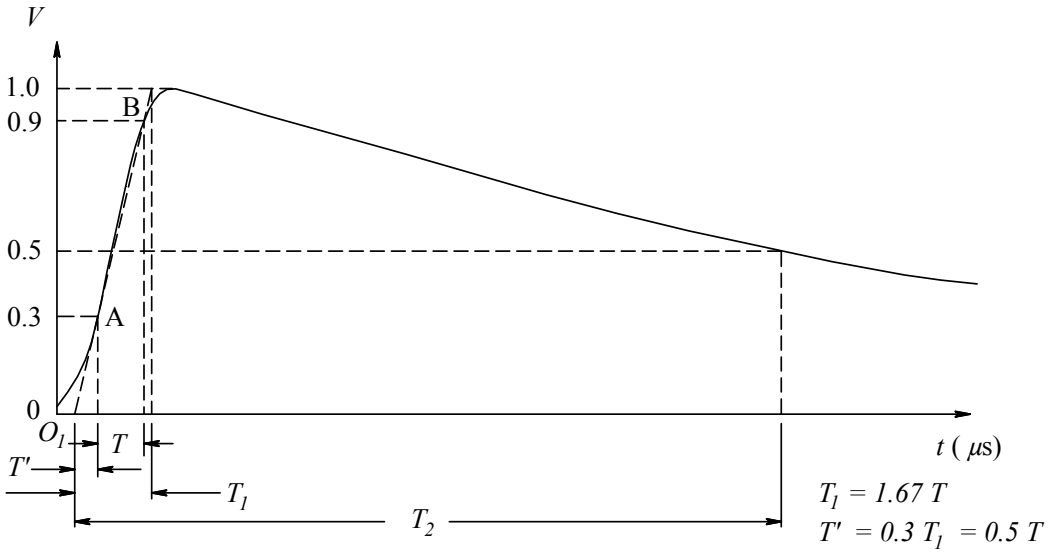


Figure 6—Full lightning impulse without oscillations or overshoots

standard lightning impulse: A full lightning impulse having a front time (T_1) of 1.2 μs and a time to half-value (T_2) of 50 μs, and is described as a 1.2/50 impulse (see Figure 6).

overshoot: the increase in amplitude of a full lightning impulse voltage caused by an oscillation at the peak.

value of the test voltage, V_t: The peak value of the test voltage curve.

recorded curve: A graphical or digital representation of the test data of an impulse voltage.

base level: The level of a record of an impulse measuring system when there is zero input to the recording instrument.

base curve: The estimate of a full lightning impulse voltage without a superimposed oscillation.

NOTE—Methods for evaluation of the base curve are given in Annex A.

residual curve: The difference between the recorded curve and the base curve.

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test voltage function: An amplitude-frequency function that defines the response of insulation to impulses with overshoot. It is given by:

$$k(f) = \frac{1}{1 + 2.2 f^2} \tag{35}$$

where

f is the frequency in megahertz. This function is shown in Figure 7.

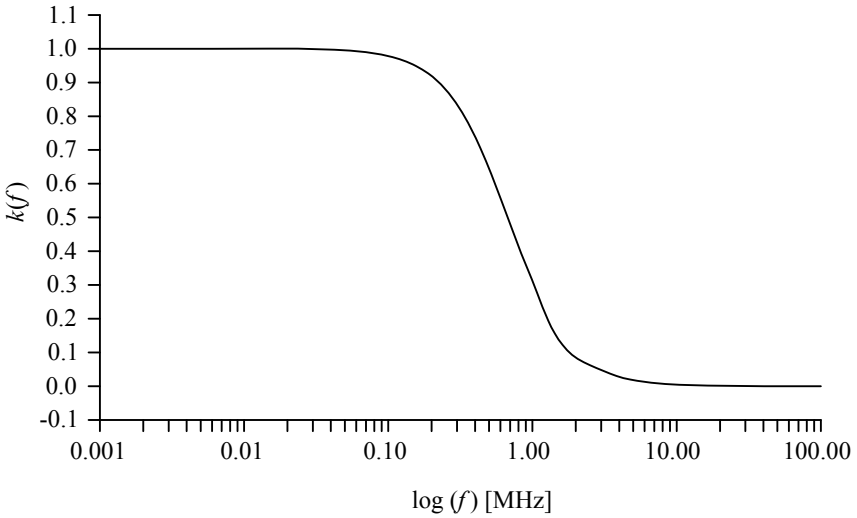


Figure 7—Test voltage function $k(f)$

test voltage curve: The summation of the base curve and the residual curve after it has been processed by a filter whose frequency response is defined by the test voltage function.

When there is no overshoot ($\beta' < 1\%$), the recorded curve is the test voltage curve.

overshoot magnitude, β: The difference in peak values between the recorded curve and the base curve.

relative overshoot magnitude, β': The ratio of the overshoot magnitude to the extreme value, usually expressed as a percentage.

extreme value of an impulse, V_e: The maximum value of the recorded curve.

extreme value of the undershoot of a chopped impulse: The maximum value measured from the base level in the opposite sense to the applied impulse (see Figure 8).

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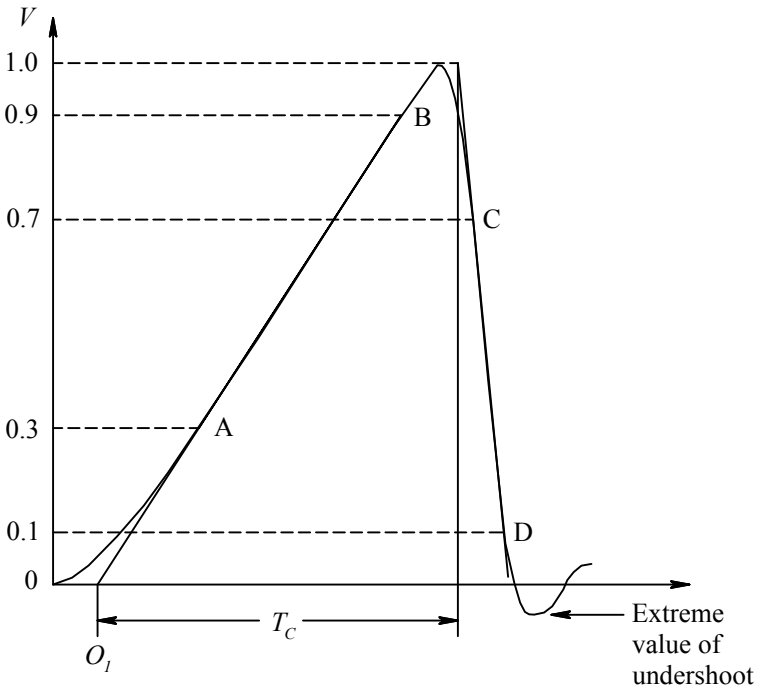


Figure 8—Front-chopped lightning impulse voltage

actual origin, *O*: The instant where the recorded curve begins a monotonic increase (or decrease).

NOTE—For digital systems, this can be evaluated by considering the standard deviation of noise on the base level. The consistency of determining the actual origin may be improved by evaluating from the peak.

virtual origin, O_1, of a lightning impulse: The intersection with the time axis of a straight line drawn through the reference points A and B on the front (see Figure 6).

front time, T_1, of a lightning impulse: A virtual parameter defined as 1.67 times the interval T between the instants when the impulse is 30% and 90% of the peak value on the test voltage curve (points A and B, Figure 6).

time to half-value, T_2, of a lightning impulse: A virtual parameter defined as the time interval between the virtual origin, O_1, and the instant when the test voltage curve has decreased to half the peak value.

chopped lightning impulse: A lightning impulse during which a disruptive discharge causes a rapid collapse of the voltage practically to zero value (see Figure 8, Figure 9, and Figure 10). The collapse can occur on the front, at the peak, or on the tail.

standard front-chopped lightning impulse: A standard lightning impulse chopped by an external gap 0.5 μs to 1 μs after the virtual origin (see Figure 8).

standard tail-chopped lightning impulse: A standard lightning impulse chopped by an external gap 2 μs to 5 μs after the virtual origin (see Figure 9).

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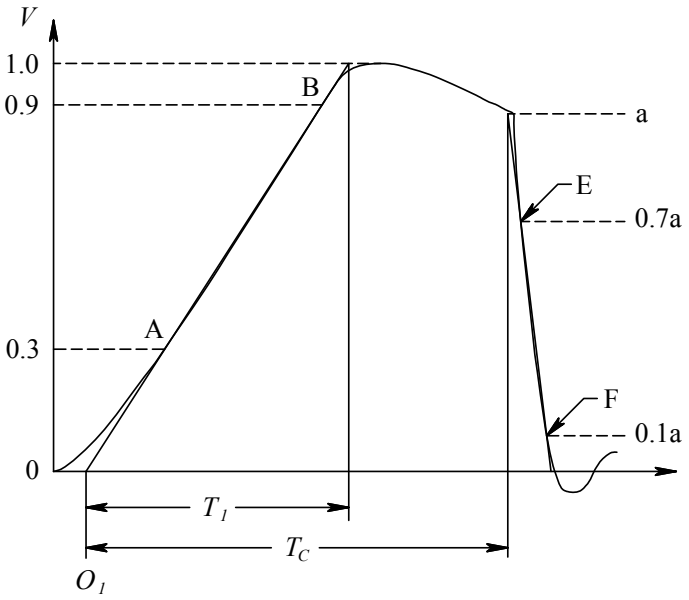


Figure 9—Tail-chopped lightning impulse voltage

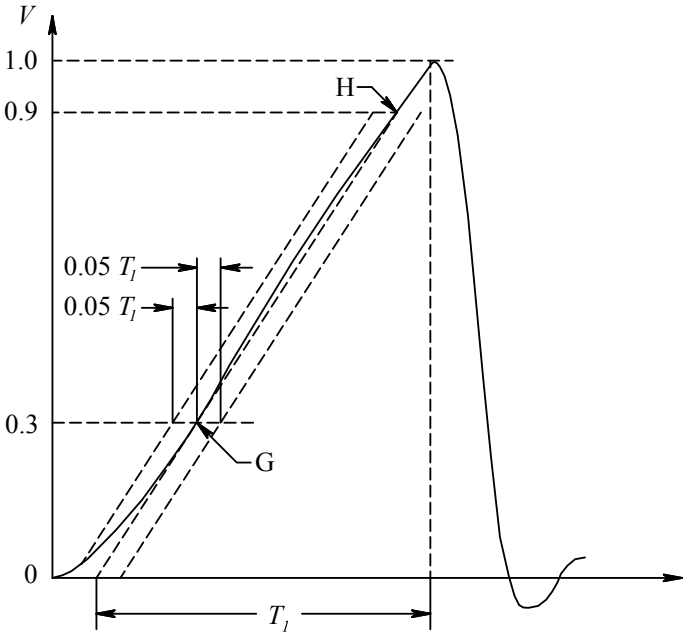


Figure 10—Linearly rising front of wave chopped impulse

instant of chopping for a front-chopped lightning impulse: The instant at which the extrapolation of the line between the 70% and 10% points on the line of collapse crosses the the peak level (see Figure 8).

instant of chopping for a tail-chopped lightning impulse: The instant at which the extrapolation of the line between the 70% and 10% points on the line of collapse crosses the level immediately before the collapse (see Figure 9).

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time to chopping, T_C, for a lightning impulse: A virtual parameter defined as the time interval between the virtual origin, O_1, and the instant of chopping.

voltage time interval, T_λ: The time interval for which the recorded curve exceeds λV_t where $0 < \lambda < 1$.

linearly rising front-chopped impulse: A voltage rising with approximately constant steepness, until it is chopped by a disruptive discharge.

To define such an impulse, the best fitting straight line is drawn through the part of the front between 30% and 90% of the peak amplitude; the intersections of this with the 30% and 90% amplitudes then being designated G and H, respectively (see Figure 10).

The impulse is defined by:

a) the peak voltage V

b) the front time T_1

c) the virtual steepness S

where

$$S = \frac{V}{T_1} \tag{36}$$

This is the slope of the straight line drawn through the points G and H, usually expressed in kilovolts per microsecond.

This chopped impulse is considered to be approximately linearly rising if the front, from 30% amplitude up to the instant of chopping, is entirely enclosed between two lines parallel to the line GH, but displaced from it in time by $\pm 0.05 \times T_1$ (see Figure 10).

NOTE—The value and the tolerance on the virtual steepness S shall be specified by the relevant apparatus standard.

switching impulse voltage: An impulse voltage with a front time longer than 20 μs.

standard switching impulse: An impulse having time to peak (T_p) of 250 μs and a time to half-value (T_2) of 2500 μs, and is described as a 250/2500 impulse (see Figure 11).

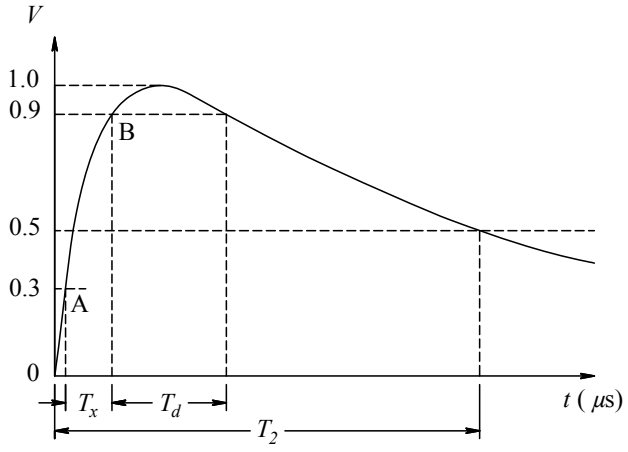


Figure 11—Switching impulse voltage

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time to peak, T_p, for a switching impulse: The time to peak, T_p, for double exponential switching impulses is defined by:

$$T_p = KT_x \tag{37}$$

where

T_x is the time interval between 30% and 90% of the peak value and the factor K is given by:

$$K = 2.42 - \left(3.08 \times 10^{-3}\right)T_x + \left(1.51 \times 10^{-4}\right)T_2 \tag{38}$$

All time parameters (T_p, T_x, and T_2) are expressed in microseconds.

This procedure for determining T_p is intended primarily for computer-aided evaluation of digital oscilloscope records using double exponential waveforms. An alternative procedure may also be used, in which T_p is the time interval between the actual origin and the instant when the voltage has reached its maximum value.

time to half-value, T_2, for a switching impulse: The time interval between the actual origin and the instant when the voltage has first decreased to half the peak value.

time above 90%, T_d, for a switching impulse: The time interval during which the impulse voltage exceeds 90% of its peak value.

time to zero, T_0, for a switching impulse: The time interval between the actual origin and the instant when the voltage has its first zero crossing.

NOTE—Specification of the time above 90% and time to zero instead of the time to half-value is found useful, for instance, when the form of the impulse is dictated by saturation phenomena in the test object or the test circuit, or where the severity of the test on important parts of internal insulation of the test object is considered to be highly dependent on these parameters. When specifying a switching impulse, only one set of parameters related to the waveshape is generally given. The particular time parameters defined should be clearly indicated by reference, for example, to a T_p/T_2 or $T_p/T_d/T_0$ impulse. This should be specified by the relevant apparatus standard.

8.2 Source requirements

8.2.1 Requirements for the test voltage

8.2.1.1 General requirements for lightning impulses

The standard lightning impulse is an impulse having a front time (T_1) of 1.2 µs and a time to half-value (T_2) of 50 µs. It is described as a 1.2/50 impulse.

In most cases, overshoot or oscillations can be limited to 5% of the peak voltage. In some cases, higher limits may have to be tolerated, but in all cases, the overshoot or oscillation shall be limited to 10%.

It is recommended that the overshoot during impulse tests be less than 5%. However, due to the addition of the test voltage factor procedure (see Annex A) for overshoot measurement, the overshoot limit may be increased to 10% to allow waveforms accepted by the historical “smooth curve” overshoot method. The test voltage factor method allows for increased accuracy in reading waveforms with overshoot. It should be noted that in some cases this increased tolerance may result in overstressing or understressing of the

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apparatus under test. Advice on overshoot tolerances for particular apparatus should be addressed by the relevant apparatus standard.

Tolerances:

a) Peak value ± 3%

b) Front time ± 30%

c) Time to half-value ± 20%

NOTE 1—It is emphasized that the tolerances on the peak value, front time, and time to half-value constitute the permitted differences between specific values and those actually recorded by measurements. These differences should be distinguished from measuring uncertainties.

NOTE 2—In specific cases, such as during tests on low impedance objects or in test circuits having large dimensions, it may be difficult to adjust the shape of the impulse within the tolerances recommended, to keep the oscillations and/or overshoot within the specified limits, or to avoid a polarity reversal. Such cases should be addressed by the relevant apparatus standard.

8.2.1.2 General requirements for chopped lightning impulses

8.2.1.2.1 Standard tail-chopped lightning impulse

A tail-chopped lightning impulse is a standard impulse chopped by an external gap 2 μs to 5 μs after the virtual origin. Other times to chopping may be specified by the relevant apparatus standard.

Tolerances:

a) Peak value ± 3%

b) Front time ± 30%

8.2.1.2.2 Linearly rising front of wave chopped impulse

A voltage rising with approximately constant steepness, until it is chopped by a disruptive discharge, is described as a linearly rising front-chopped impulse. To define such an impulse, the best-fitting straight line is drawn through the front part of the impulse between 30% and 90% of the peak amplitude; the intersections of this line with the 30% and 90% amplitudes then being designated G and H respectively (see Figure 10).

This chopped impulse is considered to be approximately linearly rising if the front, from 30% amplitude up to the instant of chopping, is entirely enclosed between two lines parallel to the line GH, but displaced from it in time by $0.05 \times T_1$ (see Figure 10). The tolerances for front-chopped impulses must be specified by the relevant apparatus standard.

8.2.1.3 General requirements for switching impulses

The standard switching impulse is an impulse having time to peak (T_p) of 250 μs and a time to half-value (T_2) of 2500 μs. It is described as a 250/2500 impulse.

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Tolerances:

a)	Peak value	± 3%
b)	Time to peak	± 20%
c)	Time to half-value	± 60%

NOTE—It is emphasized that the tolerances on the peak value, time to peak, and time to half-value constitute the permitted differences between specific values and those actually recorded by measurements. These differences should be distinguished from measuring uncertainties.

8.2.2 Generation of the test voltage

Impulse voltages are usually generated by an impulse generator consisting essentially of a number of capacitors that are charged in parallel from a direct voltage source and then discharged in series into a circuit that includes the test object and the measuring system. The general impulse shape, whether it be lightning, oscillating, or switching impulse, is controlled by selection of the resistors and or inductors included as wave shaping components in the impulse generator.

An intentionally chopped lightning impulse can be generated by using a chopping gap (such as a rod gap) described in Clause 14, which causes a disruptive discharge, or by means of an electronically triggered gap.

A chopped lightning impulse may occur because of a discharge in the internal or external insulation of a test object.

Switching impulses are usually generated by a conventional impulse generator. They can also be generated by discharging a capacitor into one winding of a transformer.

The elements of a circuit for generating switching impulses should be chosen to avoid excessive distortion of the impulse shape due to non-disruptive discharge currents in the test circuit.

During wet switching impulse tests, non-disruptive discharge currents can reach quite large values. In test circuits with high internal impedance, these currents may cause severe distortion of the voltage or even prevent a disruptive discharge from occurring. One technique to alleviate this problem is to add a front capacitor to the impulse circuit.

8.3 Measuring system requirements for approved measuring systems

Measuring systems for lightning and switching impulse voltages shall be capable of recording much higher rates of change of voltage than those used for measuring other types of high voltage. Consequently, the components of the system should be specifically designed to have an adequate transient response.

8.3.1 Measurement of the test voltage

8.3.1.1 Measurement with approved devices

The measurement of the peak value and time parameters of impulse voltages shall be made with devices in compliance with the required procedures described in 8.5.

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8.3.1.2 The sphere gap as an approved measuring device

A sphere gap with dimensions as given in Clause 14, and used in accordance with this clause, is an approved measuring device for measurement of the peak value of impulse voltages.

8.3.2 Quantities to be measured, and uncertainties required

8.3.2.1 Peak voltage measurements

The peak value of full lightning impulses shall be measured with an uncertainty of not more than ± 3%.

The peak value of lightning impulses chopped on the tail (time to chop longer than 2 μs) shall be measured with an uncertainty of not more than ± 3%. The peak value of lightning impulses chopped on the front shall be measured with an uncertainty of not more than ± 5% for time to chop of 0.5 μs to 2 μs. For time to chop shorter than 0.5 μs or for linearly rising front-chopped impulses, uncertainties larger than 5% shall be permitted, with guidance to be given by the relevant apparatus standard.

The peak value of switching impulses shall be measured with an uncertainty of not more than ± 3%.

In cases where impulses exhibit oscillations or overshoot, and in the absence of clear guidance from the relevant apparatus standard, the following methods for determining the effective or equivalent test voltage level are permitted. These methods may be used to determine the test voltage for impulse waveshapes with up to 10% overshoot.

NOTE—Prior to the use of the peak value determination methods listed below, an effort should be made to reduce the oscillations, overshoot, and distortion by adjusting circuit parameters to achieve a standard waveshape.

Case 1: If oscillation or overshoot occurs on the peak of a full impulse wave the effective or equivalent test voltage level for that impulse may be determined by using the test voltage factor method (see 8.1 and Annex A).

When the applied impulse has a double exponential form, as is usually the case when testing objects or components with a simple insulation structure such as cables, bushings, and switchgear, the effective or equivalent test voltage level may be determined by the test voltage factor method, which utilizes a double exponential curve fitting algorithm to provide a smooth base curve.

Case 2: When the applied impulse must be chopped or when a high-voltage test object failure occurs that causes a voltage collapse or chop, the test voltage should be determined by using a previous full wave test voltage factor.

In this case, the residual frequency components required for the test voltage factor computation of the impulse may be obtained from a normalized double exponential curve fit obtained from a previous full wave application on the same test object (see Annex A).

Case 3: When the applied impulse deviates significantly from a double exponential curve, the test voltage factor method can be used with a more suitable curve fitting algorithm, or as specified by the relevant apparatus standard.

Case 4: A manual method for evaluation of irregular waveshapes is given in Annex A.

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8.3.2.2 Time parameter measurements

The time parameters that define the impulse shape such as front time, time to peak, time to half value, time above 90%, and time to chop shall be measured with an uncertainty of not more than ± 10%.

No specifications for uncertainty are given regarding time parameters that define the virtual time of voltage collapse during impulse chopping, because of the rapid rate of voltage collapse.

It is also necessary to ensure that the measuring system scale factor as determined above remains constant for the time duration of the impulse being measured. The system scale factor should remain constant within 1% during the initial rise of the impulse being measured and for a time that exceeds its time to voltage peak. The system scale factor should not change by more than 5% for the longest time to half-value used in the tests. This requirement may be verified by direct comparison of the measurements of the appropriate high-voltage impulse shapes made with another measuring system that meets the requirements of this standard.

The determination of the impulse voltage duration for which the scale factor of the measuring system is valid is particularly important in the case of capacitive voltage dividers. For such dividers, a shunting resistance across the low-voltage capacitor of the divider can cause an apparent change in scale factor with duration of the applied voltage; therefore, it has to be ensured that the time constant of the low-voltage arm of the divider shall be sufficiently large compared with the longest duration of the voltage to be measured.

To meet the accuracy requirements of this standard for measurements of the longest lightning and switching impulses respectively (taking their maximum permissible tolerance into consideration), the minimum time constants should be:

a) Lightning impulse: greater than or equal to 3 ms.

b) Switching impulse: greater than or equal to 200 ms.

When the ratio of a capacitive divider is determined by measurement of the capacitances of the high-voltage and low-voltage arms, the shunting resistance across the low-voltage arm shall be removed from the circuit.

For resistive dividers, it is necessary to ensure that the temperature rise of the resistor is low enough to prevent any appreciable change in the resistance value throughout the duration of the impulses.

8.3.3 Maximum frequency to be recorded

The maximum frequency to be recorded is the highest oscillation frequency with sufficient amplitude to affect the shape of the impulse. This frequency can appear at the test object or at the high-voltage input terminal of the measuring system in a given test circuit. A conservative estimate for the maximum frequency is given by:

$$f_{\max} = \frac{c}{\left(4H_g + 4H_c\right)} MHz \tag{39}$$

where

c is 300 m/μs, the velocity of an electromagnetic wave in air

H_g is the height of the portion of the impulse generator being used (in meters)

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H_c is the height of the front capacitor (in meters)

The value of f_{max} is generally limited to 25 MHz for tests with lightning impulses. For switching impulses, the value of f_{max} is further limited by higher impedance of the impulse circuit.

8.4 Test procedures

The test procedure applicable to particular types of test objects should be specified by the relevant apparatus standard with regard to at least the following factors:

a) The required test voltage.

b) The polarity to be used, and the preferred order if both polarities are to be used.

c) The number of applications.

d) The interval between applications.

e) Other apparatus specific procedures.

f) The evaluation procedure for the test results.

The measurement of the peak value, the time parameters, and the overshoot or oscillations on the test voltage shall be made with devices that are in accordance with the requirements specified in 8.5. The measurements shall be made with the test object in the circuit and the impulse shape shall be checked for each different test object. Where a number of test objects of identical design and dimensions are tested under identical conditions, the shape need only be verified once if only the withstand voltage is of interest.

NOTE—A determination of the impulse shape by calculation from the test circuit is not considered satisfactory.

8.4.1 50% disruptive discharge voltage test

The following test methods can be used to determine V_{50} (the 50% disruptive discharge voltage) and the standard deviation:

a) The multiple level method, with n being greater than or equal to 4 voltage levels and m being greater than or equal to 10 impulses per level.

b) The up-and-down method, with m equal to 1 impulse per group and n greater than or equal to 20 useful applications.

NOTE—The term m refers to the number of impulses per voltage level; n refers to the number of voltage levels.

Details of these methods and statistical treatment of the results are given in 15.

8.4.2 Rated withstand voltage tests

The recommended procedure depends on the nature of the test: whether it involves non-self-restoring insulation only, self-restoring insulation only, or a combination of both types. The relevant apparatus standard shall specify to what category a certain test object should be referred.

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The four procedures are described in the following paragraphs. In procedure A, procedure B, and procedure C, the voltage applied to the test object is only the specified withstand value. In procedure D, several voltage levels have to be applied.

8.4.2.1 Withstand voltage test—procedure A

Three impulses of the specified shape and polarity at the rated withstand voltage level are applied to the test object. The requirements of the test are satisfied if no indication of failure is obtained, using the methods of detection specified by the relevant apparatus standard.

8.4.2.2 Withstand voltage test—procedure B

Fifteen impulses of the specified shape and polarity at the rated withstand voltage level are applied to the test object. The requirements of the test are satisfied if no more than two disruptive discharges occur in the self-restoring part of the insulation and if no indication of failure in the non-self-restoring insulation is obtained by the detection methods specified by the relevant apparatus standard.

8.4.2.3 Withstand voltage test—procedure C

Three impulses of the specified shape and polarity at the rated withstand voltage level are applied to the test object. If no disruptive discharge occurs, the test object has passed the test. If one disruptive discharge occurs in the self-restoring part of the insulation, then nine additional impulses are applied and, if no disruptive discharge occurs, the test object has passed the test.

If any evidence of failure in a non-self-restoring part of the insulation is observed with the detection methods specified by the relevant apparatus standard during any part of the test, the test object has failed to pass the test.

8.4.2.4 Withstand voltage test—procedure D

For self-restoring insulation, the 10% impulse disruptive discharge voltage, V_{10}, may be evaluated by using statistical test procedures described in 15.

These test methods permit either direct evaluation of V_{10} and V_{50}, or indirect evaluation of V_{10}. In the latter case, V_{10} is derived from the V_{50} value using the relationship:

$$V_{10} = V_{50}\left(1 - 1.3s\right) \tag{40}$$

where

s is the standard deviation of the disruptive discharge probability distribution.

The relevant apparatus standard shall specify the value to be assumed for s. The test object is deemed to be satisfactory if V_{10} is not less than the specified impulse withstand voltage.

Alternatively, the up-and-down withstand method can be used to evaluate V_{10} with m equal to seven impulses per group and at least eight useful groups. In all cases, the voltage interval between levels, ΔV, should be approximately 1.5% to 3% of the estimated value of V_{50}.

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8.4.3 Assured disruptive discharge voltage test

The procedure for an assured disruptive discharge voltage test is similar to that described in 8.4.2, except that the test object should exhibit a disruptive discharge rather than a withstand.

The relevant apparatus standard may also specify other procedures.

8.5 Type tests, acceptance tests, performance tests, and performance checks for impulse voltage measuring systems

The following tests are described to characterize the performance of an impulse voltage measuring system. See Clause 5 for descriptions of the test protocol, measurement system classifications, record of performance requirements, and explanation of terminology.

8.5.1 Type tests (verification of a new design)

The following type tests shall be performed on approved measuring systems by the manufacturer as verification of the design. It is not required that the results of these tests be kept in the owner's record of performance; however, the manufacturer of the measuring system shall maintain the test results, and shall make them available to the user of the measuring system upon mutual agreement.

The type tests for impulse voltage measuring systems include:

a) Verification of the operating temperature range (complete measuring system, major subassemblies, or on individual components).
b) Verification of duty cycle (complete measuring system, or major subassemblies).
c) Acceptance tests (see 8.5.2).

8.5.2 Acceptance tests (new systems, or after major system repair or alteration)

An acceptance test shall be performed on all approved measuring systems, with the results documented in the record of performance, in accordance with the general requirements stated in Clause 5. An acceptance test is required as a one-time test on new measuring systems, or as a follow-up test that shall be made after any major measuring system repairs or alterations.

The acceptance tests for impulse voltage measuring systems include:

a) Determination of the measuring system short-term stability.
b) Withstand voltage test.
c) Performance tests (see 8.5.3).

The measuring system manufacturer's test report may serve as a valid acceptance test result for new measuring systems.

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8.5.3 Performance tests (yearly or according to record of performance requirement)

A performance test shall be performed either on an annual basis, or at intervals specified in the record of performance for the measuring system.

The performance tests of impulse voltage measuring systems include:

a) Determine or verify the measuring system scale factor.

b) Determine or verify the scale factor linearity.

c) Determine or verify the uncertainty of time parameter measurement.

The preferred method of determining or verifying the above is by simultaneous measurements of actual test impulse voltages made with the measurement system to be evaluated with a reference measurement system that meets the requirements of this standard. When the reference measuring system is not rated for the full test voltage, alternate means are used for determining or verifying linearity.

8.5.3.1 Test for scale factor

The scale factor shall be determined or verified by comparison to a reference measuring system with a known scale factor, with overall uncertainty consistent with the requirements stated in Clause 5 and traceable to national standards.

8.5.3.1.1 Determination or verification of scale factor for complete systems

The scale factor for a complete measuring system can be determined or verified by comparison against a reference measuring system at not less than 20% of the operating voltage of the measuring system.

8.5.3.1.2 Determination or verification of scale factors for individual components

The scale factor of a measuring system can be obtained by multiplying the scale factors of the individual components of the measuring system, listed below:

a) Divider: The scale factor for a high-voltage divider shall be determined or verified by comparison against a reference measuring system at not less than 20% of the operating voltage of the divider.

b) Digital recorder (with attenuator or probe): The scale factor of a digital recorder shall be determined or verified on all operating ranges by comparison against a reference calibrator or a reference digital recorder.

8.5.3.2 Test for scale factor linearity

The linearity shall be determined or verified by one of the following methods. Linearity determination by comparison to another approved measuring system is the preferred method.

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8.5.3.2.1 Linearity determination by comparison to another approved measuring system

To qualify as an approved measuring system, the ratio of the measured voltage to the corresponding input voltage must not deviate by more than 1% from the calculated mean value of five ratios, measured at five approximately equally spaced voltages ranging from 10% to 100% of the operating range of the measuring system.

When a sphere gap is used for linearity determination, comparisons should be performed using the procedures and dimensions as given in Clause 14.

8.5.3.2.2 Linearity determination by comparison to impulse generator charging voltage

The linearity of the system under investigation shall be demonstrated up to the full test voltage by comparing the test voltage amplitudes against the impulse generator charging voltage. To qualify as an approved measuring system, the ratio of the measured voltage to the corresponding charging voltage must not deviate by more than 1% from the calculated mean value of five ratios, measured at five approximately equally spaced voltages covering the operating range of the measuring system.

The dc measuring system used in this comparison shall meet the requirements for an approved measuring system, as described in Clause 5 and Clause 7 of this standard.

8.5.3.3 Tests for uncertainty of time parameter measurements

The uncertainty of time parameter measurements shall be determined or verified by comparison to a reference measuring system, with overall uncertainty consistent with the requirements stated in Clause 5 and traceable to national standards.

This test shall be performed using waveforms comprising the shortest front time and longest tail time to be measured by the system.

8.5.4 Performance checks (at regular intervals)

A performance check of the measuring system may be performed by the user at any time between performance tests when it is deemed necessary to verify the correct function and approximate accuracy of an approved measuring system for a specific test.

The scale factor and time parameter checks for purposes of a performance check may be accomplished at any voltage up to 100% of the rated voltage of the measuring system by one of the following methods:

a) Low-voltage ratio check (scale factor check).
b) Comparison against reference divider or approved measuring system (scale factor and time parameters check).
c) Measurement of impedances (scale factor check).
d) Check of waveform parameters in a recorded test circuit configuration at a recorded charging voltage (scale factor and time parameters check).
e) Check time parameters using low-voltage waveform generators (step response measurement).

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8.6 Additional information on impulse voltage test and measurement techniques

8.6.1 Various sources of errors and precautions

8.6.1.1 Proximity effects

Most high-voltage dividers have distributed stray capacitances to ground and to neighboring conducting objects. In resistive dividers, these capacitances affect the response characteristics since they are charged and discharged through the divider resistance. In capacitive dividers, the stray capacitances affect the scale factor of the system. Consequently, the positions of nearby conducting objects relative to the voltage divider should be the same during both the comparison tests with the reference divider and the actual tests.

With capacitor type or mixed type dividers, it is generally necessary to check the scale factor of the system in the actual test arrangement, even though this scale factor has been determined independently. This is because the presence of stray capacitances can affect the scale factor.

8.6.1.2 High-voltage leads and damping resistors

For any particular measurement, the length of the lead should be stated, and it should be within the range of lengths for which the measuring system was calibrated. The position of the lead should be the same, to the extent that it is practically possible, for a test as during calibration.

The high-voltage lead of the divider should normally be connected directly to the high-voltage terminal of the test object and not to the impulse generator or any point on the interconnecting lead. This avoids inclusion of the inductive voltage drop from the lead in the measurement.

Since the test object and voltage measurement device are physically separated, it should be recognized that the voltages appearing across both are rarely identical.

A resistor having very low inductance may be inserted in the high-voltage lead to the divider to damp excessive high frequency oscillations and reflections. If the damping resistor is located close to the divider, it is considered to be part of the divider, and the damping resistor shall be taken into consideration when the scale factor of the system is determined.

8.6.2 Special procedures for impulse tests

8.6.2.1 Chop gap test procedure

During chopped lightning impulse tests, the gap used for chopping should be located as close as possible to the terminals of the test object without disrupting its electric field distribution. The inductance of the chopping circuit should be minimized by the use of the shortest possible leads to the chopping gap, and the lead length should not exceed the height of the test object.

If the undershoot during chopping exceeds 30% of the voltage at the instant of chopping, the relevant apparatus committee should be consulted for techniques that may be used to reduce the undershoot.

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8.6.2.2 Special switching impulse

When use of the standard switching impulse alone is not considered sufficient or appropriate, special impulses of either a periodic or oscillating form may be prescribed by the relevant apparatus standard.

When specifying a switching impulse, only one set of parameters related to the waveshape is generally given. The particular time parameters defined should be clearly indicated by reference, for example, to a T_p/T_2 or $T_p/T_d/T_0$ impulse.

Specification of the time above 90% instead of the time to half-value is useful when, for instance, the form of the impulse is dictated by saturation phenomena in the test object or the test circuit, or where the severity of the test on important parts of the internal insulation of the test object is considered to be highly dependent on this parameter.

8.6.3 Coaxial cable matching circuits

Various methods may be used to terminate measuring cables satisfactorily depending on the type of voltage divider being used. The circuits shown in Figure 12 are in common use.

Any measuring cable on the low-voltage side of a measuring system should be coaxial and of the high-frequency type. It is essential that the cables be matched at one or both ends to prevent reflections that might result in measurement errors. If the main cable is connected to two or more instruments at the same time, and the length of the additional connecting cables is not negligible with respect to that of the main cable, a matching device should be inserted and all cables matched. When the lengths of the additional cables are negligible, no matching devices are used and only one cable is matched.

With resistive dividers, the cable is normally matched at the instrument end, but sometimes it is matched at both ends (see Figure 12b). Any attenuator or connecting device inserted in the cable should match the cable impedance. When capacitor dividers are used, the cable is usually matched only at the divider end by connecting the matching impedance in series with the cable (see Figure 12c). Any attenuator or connecting device inserted in the cable should have as high input impedance as possible.

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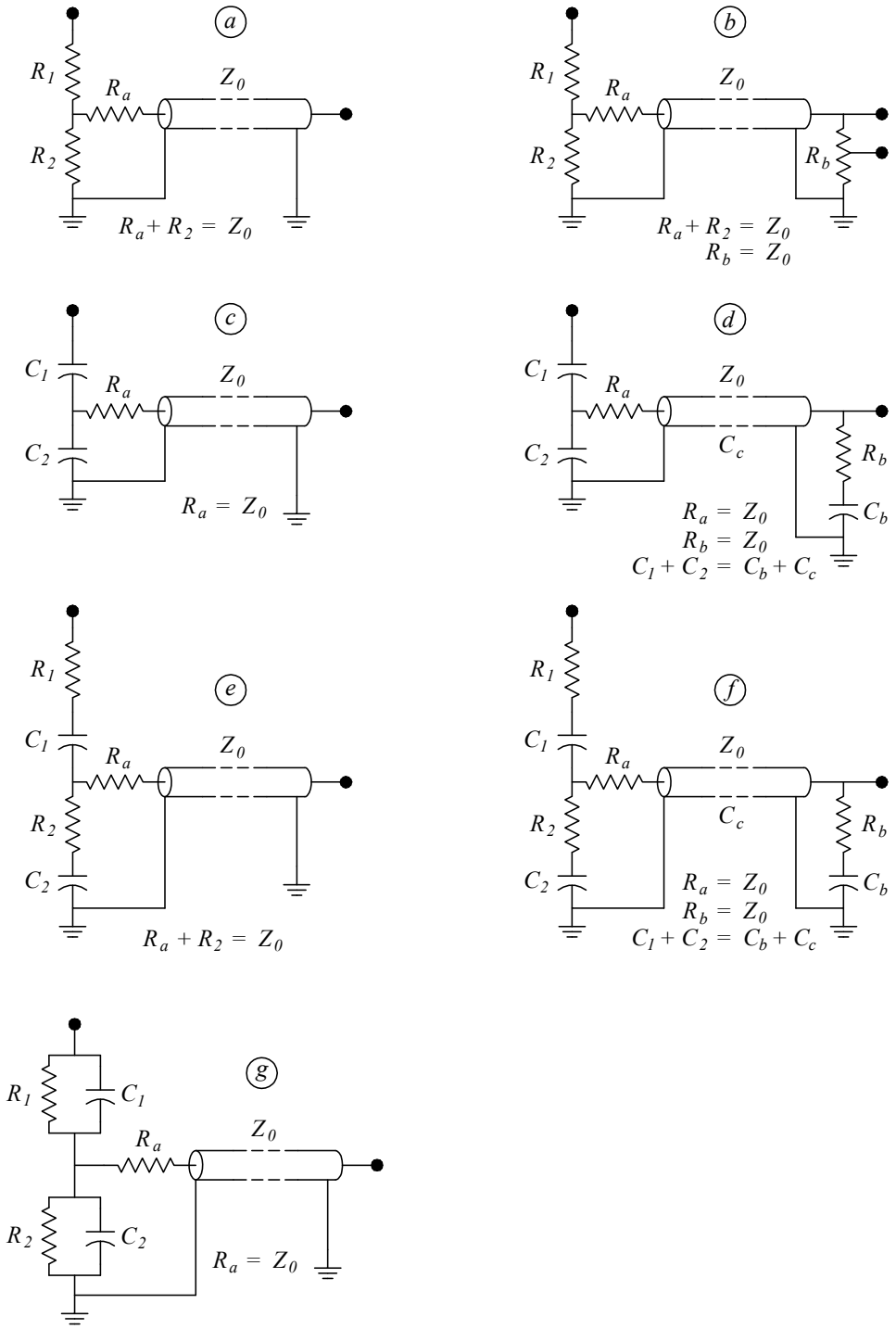


Figure 12 —Methods of matching coaxial cables

8.6.4 Probes and external attenuators

If an oscilloscope probe or attenuator is used in conjunction with the voltage divider in order to reduce the signal to a level suitable for the oscilloscope, it is essential that the probe or attenuator compensation be adjusted properly before making any measurement. The compensation is made by applying a square-wave voltage signal and altering the adjustable components of the probe or attenuator circuitry while observing

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the output signal from the probe or attenuator on the oscilloscope screen. It should be noted that the built-in square-wave generators in most oscilloscopes do not have fast enough rise times or sufficiently long direct voltage levels for compensation purposes if the probe or attenuator is to be used for the measurement of lightning impulses. It is therefore recommended that an external signal generator be used that has a rise time not greater than 10 ns and a direct voltage level of at least 1 ms duration. If the probe or attenuator is to be used in the determination of the step response of the measuring system, then the rise time of the square wave should be 10 ns or faster.

8.6.4.1 Probe scale factor

Unlike voltage dividers, the scale factor of an oscilloscope probe cannot be determined from impedance measurements. Instead, it is determined by applying a voltage that can be accurately measured by means of an external voltmeter and measuring the output voltage with the oscilloscope itself. The probe compensation has to be adjusted for optimum response before making these measurements. A single-shot step generator can be used and the direct voltage level before the application of the step is the input signal to be measured. Alternatively, an alternating voltage signal may be used, provided that its frequency is within the measuring capability of the external voltmeter. Another technique is to use a digital recorder with an impulse calibrator as defined in IEC 61083-1 (listed in Clause 2). Whichever technique is used, the probe signal should agree with the external voltmeter or the impulse calibrator to within ± 1%.

When two similar probes are being used during comparative measurements, a useful check can be performed by connecting both probes to the same input signal. The resulting waveforms should agree to within ± 0.5% for amplitude measurements and to within ± 3% for measurements of time parameters.

8.6.5 Evaluation of a measuring system by comparison method

This test may be performed at a relatively low-voltage level, approximately 200 kV to 500 kV (at least 20% of the maximum voltage to be measured), so that an independent reference system of much lower rating than that being tested may be used.

If the comparison is made with impulses of different shapes, conclusions can be drawn concerning the range of shapes for which the system is suitable. However, it is desirable that the comparison be made with the particular impulse shape to be measured. When making such a test, both systems should be connected simultaneously to ensure that the same impulse is being measured by both. There is a possibility that there may be coupling between the two systems, and precautions should be taken to minimize coupling by keeping the high-voltage measuring leads of the two systems orthogonal.

The minimum clearance from the reference voltage divider to neighboring walls and any other high-voltage apparatus should not be less than the height of the highest divider used in the comparison.

8.7 Reference voltage divider

8.7.1 Introduction

The ability of an impulse measuring system to measure time parameters and amplitudes of a particular type of impulse shall be confirmed by comparison against a reference divider, together with a demonstration of linearity up to its working voltage. The reference divider shall comply with the specifications given below, or have step response values that meet the criteria in Table 2. Refer to Annex B for the procedure used to measure the experimental step response.

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Table 2—Step response time parameters for reference dividers (in nanoseconds)

Parameter	Waveshape		
	Full and tail-chopped lightning impulses	Front-chopped lightning impulses	Switching impulses
T_N	≤ 15	≤ 15	—
T_s[a]	≤ 200	≤ 150	≤ 10 000
T_α	≤ 30	≤ 20	—
T_0	—	≤ 2.5	—

[a] The T_s requirement does not apply in the case of resistive reference dividers.

The reference measuring system shall measure the peak value of standard lightning and switching impulses with an uncertainty of not more than ± 1% and the time parameters of standard lightning and switching impulses with an uncertainty of not more than ± 5%.

The information presented in this clause pertains to the design of a 200 kV resistive voltage divider that may be used as a reference divider to check other impulse dividers.

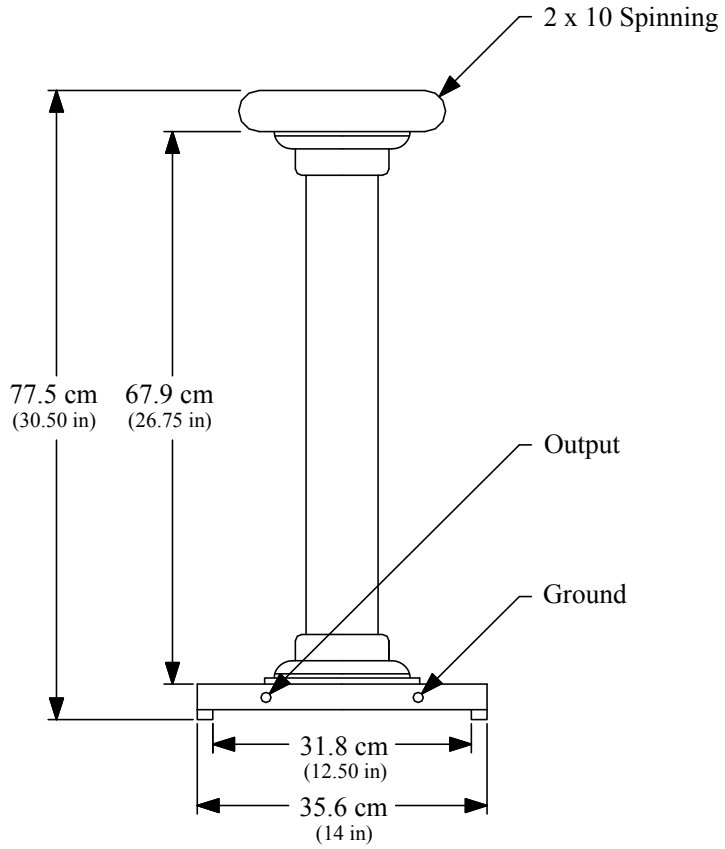
8.7.2 Overall design

The divider consists of a high-voltage arm that is comprised of two 1875 Ω resistors in series, a pair of 75 Ω termination impedances, and a measuring cable. The divider may be terminated in 50 Ω with a resulting nominal ratio of 151:1 instead of the nominal ratio of 101:1 obtained with 75 Ω terminations. Lower voltage output levels (higher ratios) may be obtained by reducing the resistance of the termination at the measurement end. However, it is important to avoid adding any additional inductance to the low-voltage arms. The high-voltage section resistors are mounted in an oil-filled tube to provide additional dielectric strength and to maintain temperature stability during repetitive tests. The design does not include grading electrodes or external damping resistance in order to provide a simplified device that any industrial laboratory can easily fabricate.

An outline drawing and schematic of the reference divider are shown in Figure 13 and Figure 14 respectively.

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NOTE—The 2 x 10 Spinning refers to a toroidal shielding electrode having an overall diameter of 254 mm (10 in) and a torial cross sectional diameter of 51 mm (2 in).

Figure 13 —Reference voltage divider outline drawing

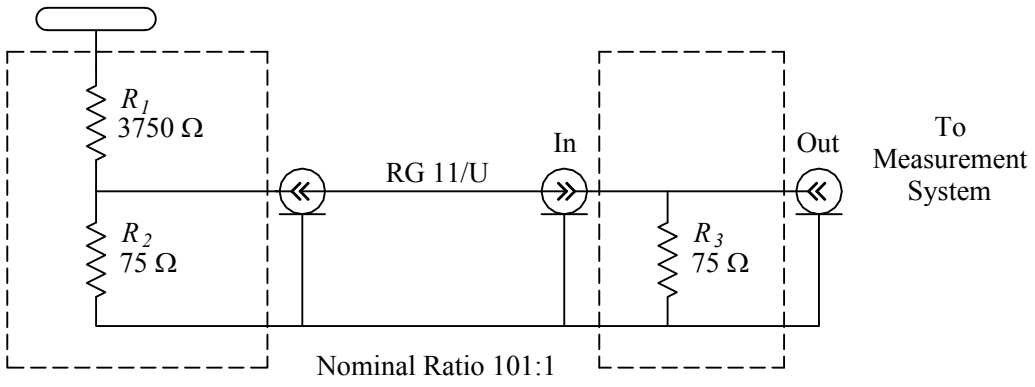


Figure 14 —Reference voltage divider schematic

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8.7.2.1 High-voltage arm resistors

The high-voltage section resistors are made of multiple layers of insulated nichrome wire wound on a round form. The winding direction is reversed after each layer to reduce the self-inductance. The winding is set up with a slight spacing between turns to improve the electrical strength. Winding data is provided in Table 3.

After winding, the resistor should be vacuum impregnated in varnish or epoxy to improve the turn-to-turn dielectric strength.

Table 3—Winding data for reference divider

Description	Details
Form length	295 mm (11.625 in)
Winding length	267 mm (10.5 in)
Wire gauge	33 AWG
Wire alloy	80/20 Ni-Cr
Resistance	42 Ω/m (12.9 Ω/ft)
Specific Gravity	8.41
Outside Insulation Diameter	0.2 mm (0.0079 in)
Bare Diameter	0.18 mm (0.0071 in)
Turns per layer	1100
Winding pitch	0.24 mm (0.0095 in)
Turns per centimeter (inch)	41.3 (105)
Layer insulation	0.13 mm (0.0005 in) polyester film tape
Total mass	37 g (1.3 oz)
Wire length	177 m (580 ft)

8.7.2.2 Low-voltage arm resistors

The low-voltage arm resistors are comprised of at least six low-inductance, thick, metal film resistors in parallel, each rated for 2 W minimum. The low-voltage resistor units should be mounted within metal enclosures for shielding, and the input and output connections can be made with coaxial connectors.

8.7.2.3 Assembly

The high-voltage arm resistors are mounted on an insulating rod that, in turn, is enclosed in a cylindrical housing. The housing is filled with mineral oil. The connection to the low-voltage side of the divider should be as short as possible to avoid adding inductance. A solid ground connection should be provided at the base.

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8.7.2.4 Measuring cable

The measuring cable should be RG11/U for systems terminated in 75 Ω or RG8/U for systems terminated in 50 Ω. The measuring cable length should be limited to 15 m (50 ft).

8.7.2.5 High-voltage lead

The length, diameter, and position of the high-voltage lead for the reference divider shall be unchanged whenever the divider is used to measure impulses, either independently or simultaneously with other measurement systems.

8.7.2.6 Response parameters

The resulting divider should have response parameters in accordance with Table 2. These response time values are given for guidance only.

9. Test and measurements with impulse current

9.1 Terms used to characterize impulse currents

impulse current: Two types of impulse currents are considered in this standard. The first type has a shape that increases from zero to a peak value in a relatively short time and thereafter decreases to zero, either approximately exponentially or in the manner of a heavily damped sine wave. This type is defined by the front time T_1 and the time to half-value T_2.

The second type has an approximately rectangular shape and is defined by the duration of the peak T_d and the total duration T_t.

value of the test current: The value of the test current is normally defined by its peak value. With some test circuits, overshoot or oscillations may be present on the current. The relevant apparatus standard should specify whether the value of the test current should be defined by the actual peak or by a smooth curve drawn through the oscillations.

virtual front time (T_1): The virtual front time, T_1, is defined as 1.25 times the interval between the instants when the impulse is 10% and 90% of the peak value (point C and point B as shown in Figure 15). If oscillations are present on the front, the 10% and 90% values should be derived from a mean curve drawn through these oscillations in a manner analogous to that used for oscillatory lightning impulses (see 8.3.2.1 and Annex A).

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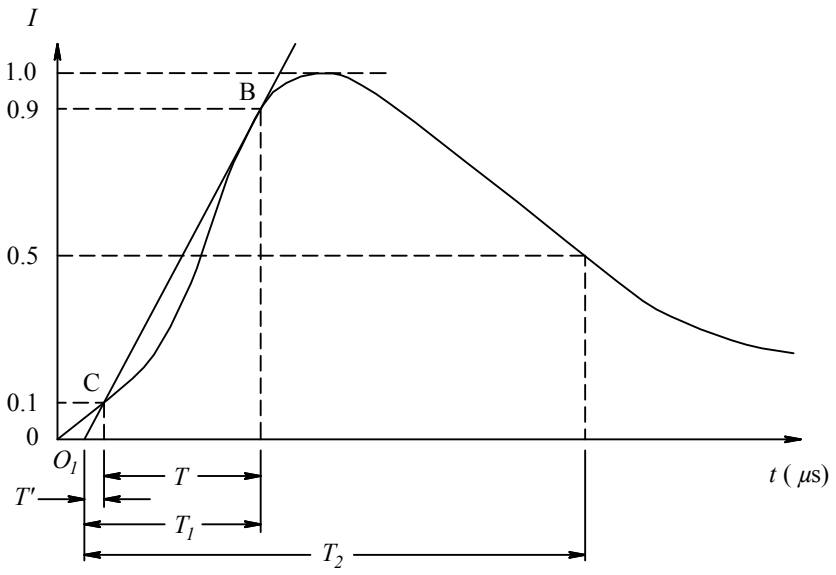


Figure 15 —Exponential impulse current

virtual origin (O_1): The virtual origin, O_1, of an impulse current precedes by 0.1 T_1 that instant at which the current attains 10% of its peak value. For an analog oscilloscope or digital impulse recorder having linear time scales, this is the intersection with the time axis of a straight line drawn through the 10% and 90% points on the front.

virtual time to half-value (T_2): The time interval between the virtual origin and the instant on the tail at which the current has decreased to half the peak value.

duration of peak of a rectangular impulse current (T_d): The time during which the current is greater than 90% of the peak value as shown in Figure 16.

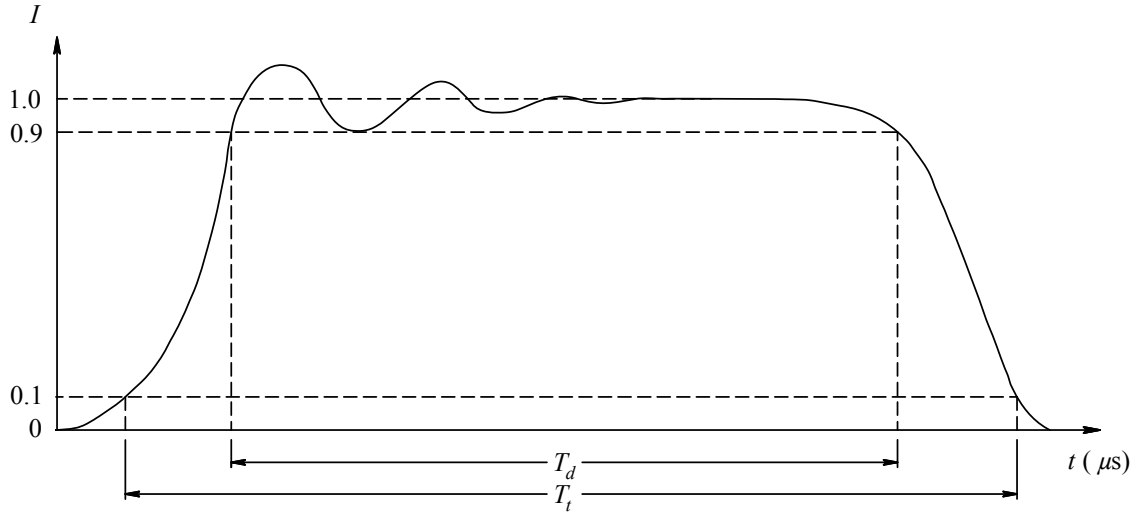


Figure 16 — Rectangular impulse current

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total duration of a rectangular impulse current (T_t): The time during which the current is greater than 10% of its peak value. If oscillations are present on the front, a mean curve should be drawn in order to determine the time at which the 10% value is reached.

standard impulse currents: Commonly used exponential impulse currents are:

a) The 1/20 impulse with virtual front time of 1 μs and time of half-value of 20 μs.

b) The 4/10 impulse with virtual front time of 4 μs and time of half-value of 10 μs.

c) The 8/20 impulse with virtual front time of 8 μs and time to half-value of 20 μs.

d) The 30/80 impulse with virtual front time of 30 μs and time of half-value of 80 μs.

Rectangular impulse currents have peak durations of 500 μs, 1000 μs, or 2000 μs, and total durations from 2000 μs to 3200 μs.

Other shapes may be defined by the relevant apparatus standard.

9.2 Source requirements

9.2.1 Requirements for the test current

If not otherwise specified by a relevant apparatus standard, and provided that the measuring system meets the requirements of 9.3.2, standard waveform tolerances for exponential impulse currents are given in 9.2.1.1, and for rectangular impulse currents in 9.2.1.2.

9.2.1.1 General requirements for exponential current impulses

Tolerances for 1/20, 4/10, 8/20, and 8/10 30/80 impulses:

a)	Peak value	± 10%
b)	Virtual front time	± 10%
c)	Virtual time to half-value	± 10%

Overshoot or oscillations are tolerated, provided that their single peak amplitude in the neighborhood of the peak of the impulse is not more than 5% of the peak value. Any polarity reversal (undershoot) after the current has fallen to zero shall not be more than 20% of the peak value.

9.2.1.2 General requirements for rectangular impulses

Tolerances for rectangular impulses:

a)	Peak value	+ 20%, – 0%
b)	Duration of peak	+ 20%, – 0%

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An overshoot or oscillation is tolerated, provided that the single crest amplitude is not more than 10% of the peak value. The total duration of a rectangular impulse should not be larger than 1.5 times the duration of the peak, and the polarity reversal should be limited to 10% of the peak value, or as specified by the relevant apparatus standard.

9.3 Measuring system requirements for approved measuring systems

Measuring systems for impulse current must be capable of handling very high currents (on the order of hundreds of thousands of amperes). Because of the very rapid rates of change of current involved, careful attention shall be paid in the design of the components to ensure that the inductance of the impulse current measurement circuit is kept low. It is also important that the insertion of the measuring system into the test circuit should not introduce unnecessary impedances.

9.3.1 Measurement of the test current

9.3.1.1 Measurement with approved devices

The measurement of the peak value and time parameters of impulse currents shall be made with devices in compliance with the required procedures described in 9.5.

9.3.1.2 Commonly used measuring systems

The following are typical systems used for measuring impulse currents:

a) Shunt with analog or digital oscilloscope, digital impulse recorder, or peak reading instrument.
b) Current transformer with analog or digital oscilloscope, digital impulse recorder, or peak reading instrument.
c) Rogowski coil with analog or digital oscilloscope, digital impulse recorder, or peak reading instrument.

9.3.2 Quantities to be measured, and uncertainties required

9.3.2.1 Peak current measurements

The peak value of standard impulse currents shall be measured with an uncertainty of not more than ± 3%.

This requirement will be met if the system meets the performance requirements described in 9.5, and the performance tests specified show that the resistance of the shunt or, alternatively, the ratio of the current transformer is stable and known with an uncertainty of not more than ± 1%.

9.3.2.2 Time parameter measurements

The time parameters that define the impulse shape such as front time, time to half value, and time above 90% shall be measured with an uncertainty of not more than ± 10%.

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In addition, the measuring system shall be capable of detecting oscillations superimposed on a current impulse.

These requirements will be met if the system meets the performance requirements described in 9.5, and the specified performance tests show that the response time T of the system complies with the requirements given in Table 4.

Table 4—Impulse current system response requirements

Impulse to be measured	Requirements (ns)
4/10 μs	$T < 800$
8/20 μs	$T < 1600$
250 μs to 2000 μs (rectangular)	$T < 1000$
Power transformer neutral current	$T < 100$

The time to half-value of the response should be considerably longer than the front time of the impulse to be measured.

Guidance on methods for determining the response of shunts is given in 9.6.3. In general, the unit step response of shunts does not take the form of a damped oscillation.

NOTE—Shunts should preferably be the coaxial tubular type described in 9.6.1. Shunts of other types, or other types of devices such as wide band transformers, may be used provided that they fulfill the requirements.

9.4 Test Procedures

The test procedure applicable to particular types of test objects should be specified by the relevant apparatus standard.

9.5 Type tests, acceptance tests, performance tests, and performance checks for impulse current measuring systems

The following tests are described to characterize the performance of an impulse current measuring system. See Clause 5 for descriptions of the measurement system classifications, record of performance requirements and explanation of terminology.

9.5.1 Type tests (verification of a new design)

The following type tests shall be performed on approved measuring systems by the manufacturer as verification of the design. It is not required that the results of these tests be kept in the owner's record of performance; however, the manufacturer of the measuring system shall maintain the test results, and shall make them available to the user of the measuring system upon mutual agreement.

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The type tests for impulse current measuring systems include:

a) Verification of the operating temperature range (complete measuring system, major subassemblies, or on individual components).
b) Verification of duty cycle (complete measuring system, or major subassemblies).
c) Acceptance tests (see 9.5.2).

9.5.2 Acceptance tests (new systems, or after major system repair or alteration)

An acceptance test shall be performed on all approved measuring systems, with the results documented in the record of performance, in accordance with the general requirements stated in Clause 5. An acceptance test is required as a one-time test on new measuring systems, or as a follow-up test that shall be made after any major measuring system repairs or alterations.

The acceptance tests for impulse current measuring systems include:

a) Determination of the measuring system short-term stability.
b) Withstand current test.
c) Performance tests (see 9.5.3).

The measuring system manufacturer's test report may serve as a valid acceptance test result for new measuring systems.

9.5.3 Performance tests (yearly or according to record of performance requirement)

A performance test shall be performed either on an annual basis, or at intervals specified in the record of performance for the measuring system.

The performance tests of impulse current measuring systems include:

a) Determine or verify the measuring system scale factor.
b) Determine or verify the scale factor linearity.
c) Determine or verify the uncertainty of time parameter measurement.

The preferred method of determining or verifying the above is by simultaneous measurements of actual test impulse currents made with the measurement system to be evaluated with a reference measurement system that meets the requirements of this standard. When the reference measuring system is not rated for the full test current, alternate means are used for determining or verifying linearity.

9.5.3.1 Test for scale factor

The scale factor shall be determined or verified by comparison to a reference measuring system with a known scale factor, with overall uncertainty consistent with the requirements stated in Clause 5 and traceable to national standards.

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9.5.3.1.1 Determination or verification of scale factor for complete systems

The scale factor for a complete measuring system can be determined or verified by comparison against a reference measuring system at not less than 20% of the operating current of the measuring system.

9.5.3.1.2 Determination or verification of scale factors for individual components

The scale factor of a measuring system can be obtained by multiplying the scale factors of the individual components of the measuring system, listed below:

a) Shunt or current transformer: The scale factor for a shunt or current transformer shall be determined or verified by comparison against a reference measuring system at not less than 20% of the operating current of the device.

b) Digital recorder (with attenuator or probe): The scale factor of a digital recorder shall be determined or verified on all operating ranges by comparison against a reference calibrator or a reference digital recorder.

9.5.3.2 Test for scale factor linearity

The linearity shall be determined or verified by one of the following methods. Linearity determination by comparison to another approved measuring system is the preferred method.

9.5.3.2.1 Linearity determination by comparison to another approved measuring system

To qualify as an approved measuring system, the ratio of the measured current to the corresponding input current must not deviate by more than 1% from the calculated mean value of five ratios, measured at five approximately equally spaced currents ranging from 10% to 100% of the operating range of the measuring system.

9.5.3.2.2 Linearity determination by comparison to impulse generator charging voltage

The linearity of the system under investigation shall be demonstrated up to the full test current by comparing the test current amplitudes against the current impulse generator charging voltage. To qualify as an approved measuring system, the ratio of the measured current to the corresponding charging voltage must not deviate by more than 1% from the calculated mean value of five ratios, measured at five approximately equally spaced currents covering the operating range of the measuring system.

The dc measuring system used in this comparison shall meet the requirements for an approved measuring system, as described in Clause 5 and Clause 7 of this standard.

9.5.3.3 Tests for uncertainty of time parameter measurements

The uncertainty of time parameter measurements shall be determined or verified by comparison to a reference measuring system, with overall uncertainty consistent with the requirements stated in Clause 5 and traceable to national standards.

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This test shall be performed using waveforms comprising the shortest front time and longest tail time to be measured by the system.

9.5.4 Performance checks (at regular intervals)

A performance check of the measuring system may be performed by the user at any time between performance tests when it is deemed necessary to verify the correct function and approximate accuracy of an approved measuring system for a specific test.

The scale factor check for purposes of a performance check may be accomplished at any current up to 100% of the rated current of the measuring system by one of the following methods:

a) Low current ratio check (scale factor check).
b) Comparison against reference divider or approved measuring system (scale factor and time parameters check).
c) Measurement of shunt impedances (scale factor check).
d) Check of waveform parameters in a recorded test circuit configuration at a recorded charging voltage (scale factor and time parameters check).
e) Check time parameters using low current waveform generators.

9.6 Additional information on impulse current measurement techniques

9.6.1 Measuring system components for impulse current measuring systems

Many of the components of an impulse current measuring system are the same as those used in impulse voltage measuring systems, and they should meet the same requirements as outlined in the appropriate parts of Clause 8. The following components are specifically used in current measuring systems:

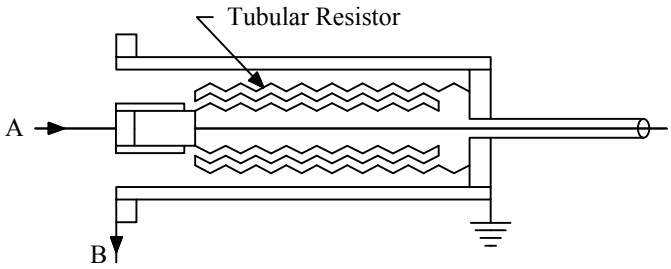
a) *Shunts.* The most commonly used form of shunt is that having a tubular construction. The construction features of some examples of this type of shunt are shown in Figure 17. The resistance material must be nonmagnetic with a low temperature coefficient of resistance to avoid errors when measuring high impulse currents.
b) *Current transformers.* Special wide-band current transformers can be used for the measurement of short duration impulses. They have advantages over shunts since they permit isolation from ground and hence can be arbitrarily located in the current circuit.
c) *Rogowski Coils.* Rogowski Coils (RC) provide an output voltage that is proportional to the rate of change of measured current enclosed by the sensor. To obtain the measured current, the RC output voltage must be integrated. RC sensors have the following characteristics: Wide measurement range (the same coil can measure currents from 1 A to over 100 kA), frequency response linear up to 10 MHz (higher frequency response possible with special designs), window-type design provides

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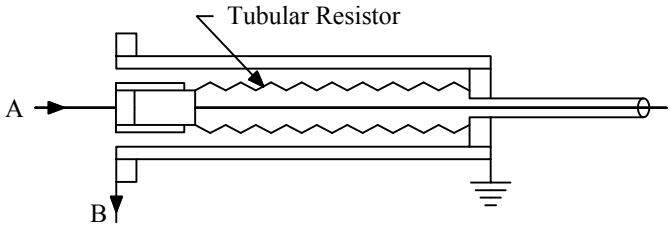
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unlimited short-circuit withstand, and Galvanic isolation from the primary conductors (similar to current transformers).

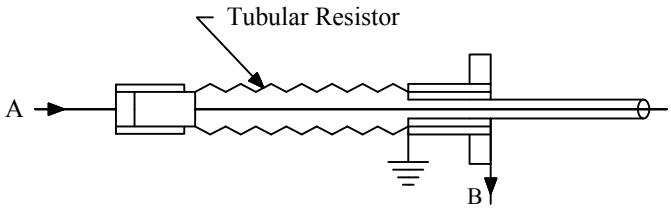
NOTE—The common grounding of the voltage and current metering is important in high-voltage measurements. Any difference between the voltage and current reference grounds will be applied across the recorder input channels and can cause measurement errors (see 9.6.4).



a) Multiple tube, coaxial return



b) Coaxial return



c) Noncoaxial return

Figure 17 —Tubular shunts for impulse current measurements (the impulse current flows from point A to point B)

9.6.2 Measurement of voltage during tests with impulse currents

Voltages developed across the test object during tests with impulse currents should be measured with an approved impulse voltage measuring system, in compliance with the procedures and requirements given in Clause 5 and Clause 8.

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The impulse current may induce appreciable voltages in the voltage measuring circuit, causing significant errors. As a check, it is therefore recommended that the lead that normally joins the voltage divider to the live end of the test object should be disconnected from this point and connected instead to the grounded end of the test object, while maintaining approximately the same loop. Alternatively, the test object may be short-circuited or replaced by a solid metal conductor.

The voltage measured under any of these conditions when the impulse current generator is discharged should be less than 0.5% of the voltage across the test object. Both measurements should be taken at the time when the voltage across the test object is at its maximum value.

9.6.3 Step response of current measuring systems

The response time of a current measuring system has to be determined experimentally; however, the method outlined below for calculating the response time of tubular shunts may prove useful in design.

Tubular resistance shunts usually have an aperiodic type of step response, and if the actual zero is used, the response time is given by:

$$T = \left(\frac{\mu_0}{6}\right) \times \left(\frac{d^2}{\rho}\right) \tag{41}$$

where

μ_o is the permeability of free space, ($4\pi \times 10^{-7}$ H/m)

T is the response time (in seconds)

d is the wall thickness of the resistor (in meters)

ρ is the resistivity of the tube (in ohm-meters)

However, due to the use of virtual origin (O_1), the response time is determined more accurately by:

$$T = \left(\frac{\mu_0}{8}\right) \times \left(\frac{d^2}{\rho}\right) \tag{42}$$

NOTE—The response of tubular shunts may be improved by including a compensating network in the part of the shunt that provides the output voltage signal. Such a compensating network may be magnetically coupled with the current carrying part of the shunt.

The rise time rating of a current transformer can be checked through the use of a pulse generator and oscilloscope. These instruments should be fast enough to generate and measure pulses representative of the impulse frequencies. One method of performing this test is shown in Figure 18.

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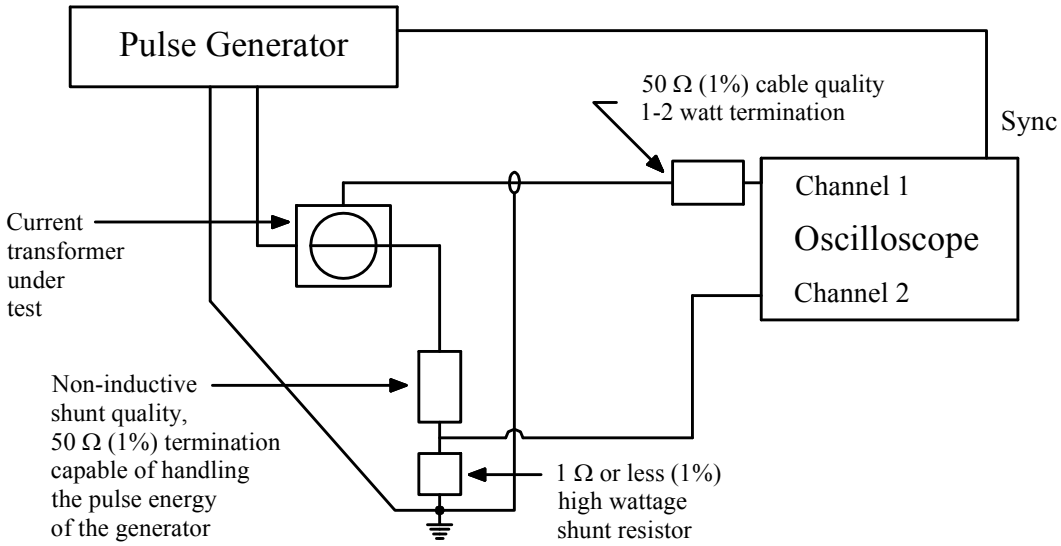


Figure 18 —Circuit for checking the rise time of a current transformer

9.6.3.1 Experimental determination of the step response

To determine the response time of a current measuring system, a step of current is applied to the system and the resulting response is treated in the same manner as outlined in Annex B for impulse voltage systems. However, the response time obtained by integrating the experimental step response is the true response time of the system and needs no correction, since there are no long leads associated with its determination.

The basic difference between the methods of obtaining the step response for current measuring systems and for voltage measuring systems is that the latter is taken using a zero-impedance source, whereas the current responses should be taken with an infinite impedance source. This is not practical, but it is generally satisfactory if the impedance of the step generator is very large compared with the impedance of the current measuring system.

A practical form of step generator is a charged cable or transmission line that is switched onto the measuring system as illustrated in Figure 19. When the switch is closed, a current step with amplitude equal to the quotient of the charging voltage divided by the cable surge impedance will be applied to the measuring system. The cable has to be long enough to ensure that the response of the measuring system has settled before a reflection from the opposite end of the cable arrives at the switch. This method is similar to that for obtaining the step response of a voltage measuring system (see Annex B), the difference in this case being that the switch generates the step by short-circuiting the output of a charged system. Because of the similarity of the two methods, the same types of switches are used and the same conditions regarding amplification apply.

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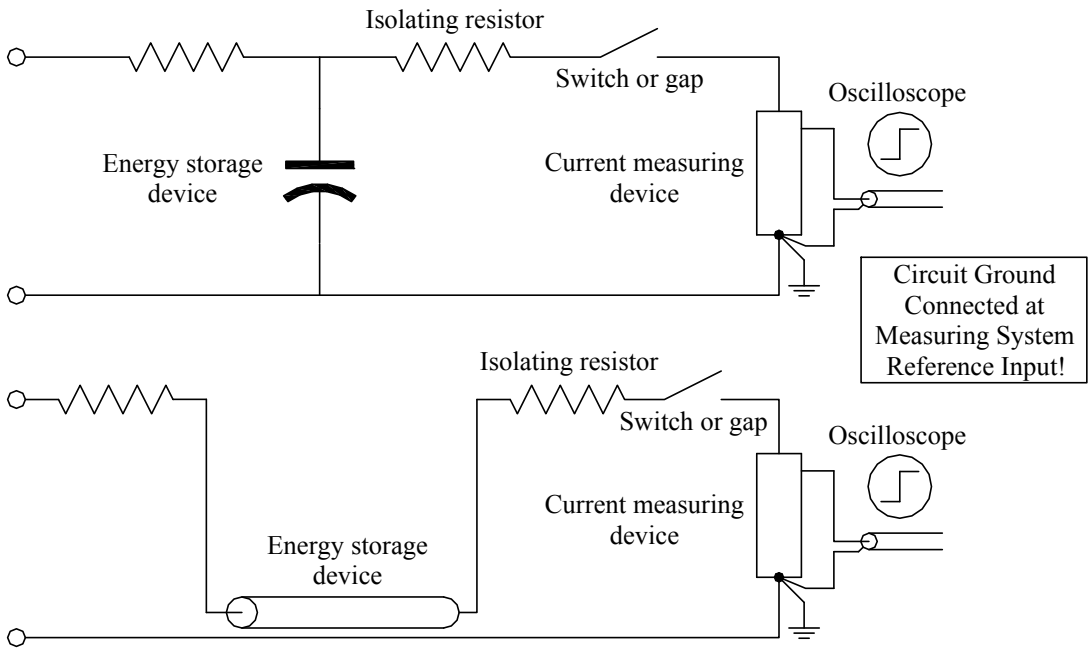


Figure 19 —Impulse current step generator connections

9.6.4 Various sources of error and precautions

In circuits where high-current impulses occur, the voltage drops on even short lengths of conductor may be considerable. Precautions are necessary to ensure that these do not result in measurement errors and that the grounding of test circuits is such that damage to the insulation of measuring or recording instruments does not occur.

Stray magnetic fields may also cause measurement errors that can be detected by altering the arrangement of conductors. Some digital oscilloscopes may require shielding before accurate measurements can be made near the magnetic fields generated during high-current impulses. This can be checked on a dual channel oscilloscope by recording the current on one channel and leaving the second channel in recording mode, but not connected to the voltage metering. If, after a current impulse, the second channel displays a signal with a magnitude greater than 1% of full screen value, the oscilloscope will require shielding to perform accurate measurements.

In addition, some specific precautions should be taken depending on the use of either shunts or current transformers.

a) *Shunts.* Care should be taken to ensure that the resistance of the shunt does not change appreciably with heating caused by the impulses being measured. The shunt should be designed with a sufficient thermal capacity to prevent permanent damage in case of failure of a series impedance, such as a test object or a damping resistor.

b) *Current transformers.* These are not capable of transferring direct voltage components. The amplitude step of the response of a current transformer decreases with time, and the rate of decrease is determined by the ratio of mutual inductance and burden resistance. The operating range of current

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transformers with magnetic cores is limited by core saturation. In order to avoid saturation, the maximum charge flowing in any given direction should not exceed the rated ampere-second product of the transformer. The usable rise time rating of the current transformer should be five times faster than the wave being measured.

10. Combined voltage and composite voltage tests

10.1 Combined voltage tests

A combined voltage test is one in which two separate sources, generating voltages against earth, are connected to two terminals of the test object (e.g., an open circuit breaker, as shown in Figure 20). In such a test, any two of lightning impulse, switching impulse, direct or power frequency alternating voltages may be combined.

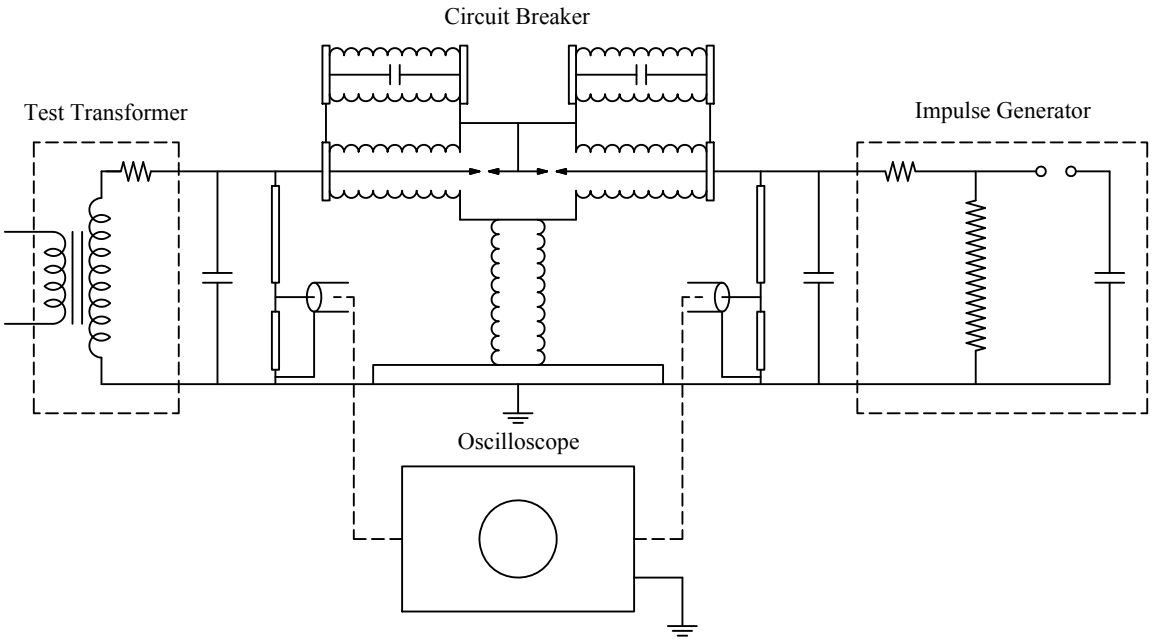


Figure 20 — Typical test circuit for combined tests

The test voltage is characterized by its amplitude, a time delay Δt, the waveshape, peak value, and polarity of each component.

When combined voltage tests are performed on switchgear, they are intended to simulate conditions in which one terminal of the open switch is energized at the specified power frequency voltage, and the other terminal is subjected to either a lightning or switching impulse voltage. The test circuit shall simulate this situation on both internal and external insulation. In special cases, the relevant apparatus standard may permit power-frequency voltages to be simulated by switching impulses of suitable shape.

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10.1.1 Value of the test voltage, *V*

The value of the test voltage, *V*, is the maximum potential difference between the energized terminals of the test object (see Figure 21).

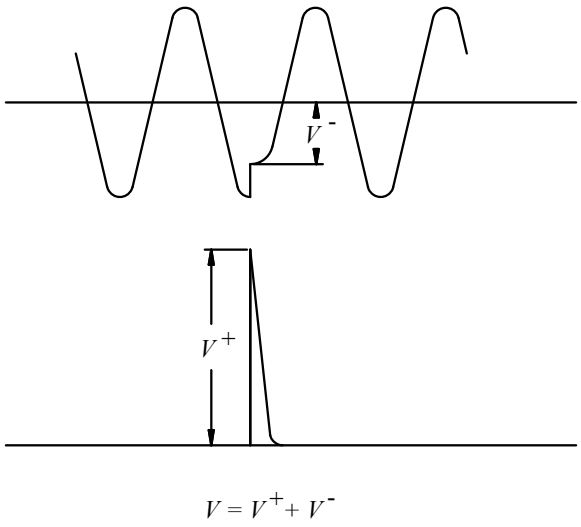


Figure 21 —Voltage waves during combined voltage tests giving a value for the test voltage, *V*

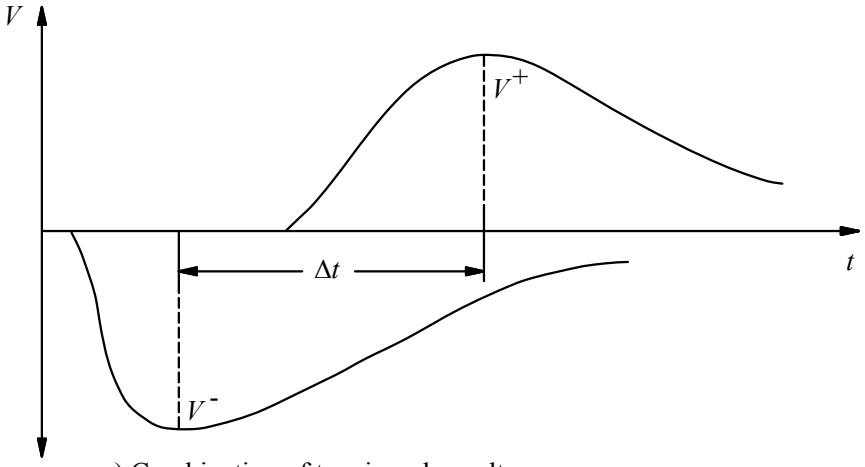
10.1.2 Time delay, Δ*t*

The time delay, Δ*t*, of a combined voltage is the time interval between the instants when its components reach their peak values, measured from the instant of a negative peak (see Figure 22). It has a tolerance of $\pm 0.05 \times T_{p\max}$, where T_p is the time to peak or the front time for an impulse and a quarter cycle for an alternating voltage, and $T_{p\max}$ is the larger of the values of T_p for the two components.

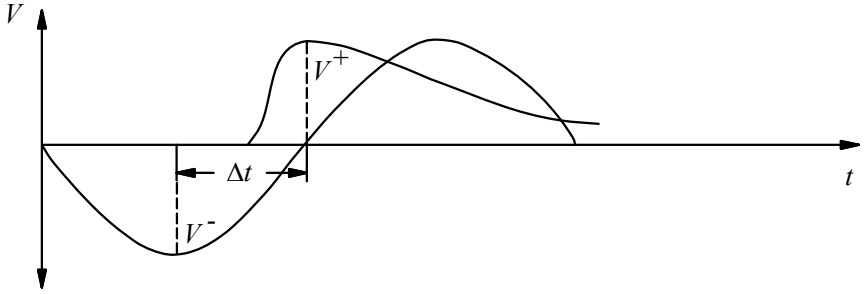
Two voltages of a combined impulse voltage test are said to be synchronous when their time delay, Δ*t*, is zero, within the prescribed tolerance.

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a) Combination of two impulse voltages



b) Combination of an impulse voltage and a power frequency alternating voltage

Figure 22 —Definition of time delay, Δt

10.1.3 Actual voltage shapes

Due to the coupling between the two generating systems, the shapes and amplitudes of the two components of a combined voltage test differ from those produced by the same sources used separately. They shall therefore be measured in combination, preferably by means of separate measuring systems against earth.

Each measuring system shall be suitable for measuring the waveshape of both of the components in order to avoid errors in recording their mutual influence.

The maximum permissible deviations from the prescribed voltage shape shall be specified by the relevant apparatus standard.

NOTE—It should be taken into account that in the case of a disruptive discharge occurring in a combined voltage test, both the voltage sources will act directly against each other if there are no additional protective elements (e.g., resistors, capacitors, inductors, or protective gaps) in the circuit. In any case, the voltage distribution between the two voltage sources will change completely when there is a disruptive discharge.

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10.1.4 Arrangement of the test object

The arrangement of the test object, particularly with respect to the earthed structures, shall be specified by the relevant apparatus standard.

10.1.5 Atmospheric correction factors

In a combined voltage test, the atmospheric correction factors relative to the component of highest value shall be applied to the test voltage value.

10.2 Composite voltage tests

A composite voltage is the voltage resulting from two different voltage sources suitably connected, applied at one terminal of the test object against earth.

The definition of its parameters is left to the relevant apparatus standard.

NOTE—Composite tests may also be performed by applying voltage and impulse-current sources to the test object.

11. Tests in different ambient conditions

11.1 Dry tests

The test object shall be dry and clean. If not otherwise specified by the relevant apparatus standard, the test should be made at ambient temperature, and the procedure for voltage application should be as specified in Clause 6, Clause 7, Clause 8, and Clause 9.

11.2 Wet tests

Since natural rain cannot be duplicated, the wet test is intended to provide a laboratory benchmark relating performance of equipment under specified precipitation conditions. The specifications for various wet test procedures are given in Table 5.

Three precipitation rates and two resistivities are found in Table 5. They appear under the headings “Standard test procedure,” “Previous European practice,” and “Previous practice in USA.” The conditions for “European practice” and “Practice in USA” are earlier test methods. They were recommended for tests with all types of test voltages and on all types of apparatus designed for outdoor use, and they have been in use for tests with alternating voltage on apparatus up to about 400 kV system voltage. Many test data obtained by these methods exist. Their use is recommended only when direct comparison is required. The use of these procedures shall be limited to specific requirements or agreements between the manufacturer and the purchaser. Wetting procedures to be followed are covered in 11.2.3.

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Table 5—Precipitation conditions (standard and conventional procedures)

Procedure	Precipitation rate (mm/min)			Collected water parameters		Wet withstand test duration(s)
	Vertical component	Horizontal component	Limits for any individual measurement	Temperature (°C)	Resistivity ohm-m [μS/cm]	
Standard test procedure	1.0 to 2.0	1.0 to 2.0	± 0.5 from average	Ambient ± 15	100 ± 15	60
Previous European practice	3 ± 0.3	–	3 ± 0.75	Ambient ± 15	100 ± 10	60
Previous practice in USA	5 ± 0.5	–	5 ± 1.25	Ambient ± 15	178 ± 27	10

11.2.1 Preparation of test object

The test object should be carefully cleaned by washing with water to which a neutral detergent, such as trisodium phosphate (Na_3PO_3), has been added and then rinsed with clean water. It shall not be touched subsequently by hand. Usually, the insulating surfaces can be considered sufficiently clean and free of grease or other contaminating material if large continuous wet areas are observed during wetting.

11.2.2 Standard wet test

The precipitation conditions in Table 5 under "Standard test procedure" are recommended for tests with all types of test voltages, and on all types of apparatus designed for outdoor use.

11.2.3 Wet test wetting procedure

The test object should be sprayed with water, of prescribed resistivity, falling on it as droplets and directed so that the vertical and horizontal components of the spray intensity are approximately equal. These intensities are measured with a divided collecting vessel having openings of 100 cm^2 to 750 cm^2, one horizontal and one vertical, the vertical opening facing the spray.

The collecting vessel should be placed close to the test object, but in a position so as to avoid collecting droplets or splashes from it. During the measuring period, the collecting vessel should be moved slowly over a sufficient area to average out the effect of non-uniformities of the spray from individual nozzles. The relevant apparatus standard shall specify the position of the test object relative to the vertical and horizontal rain components.

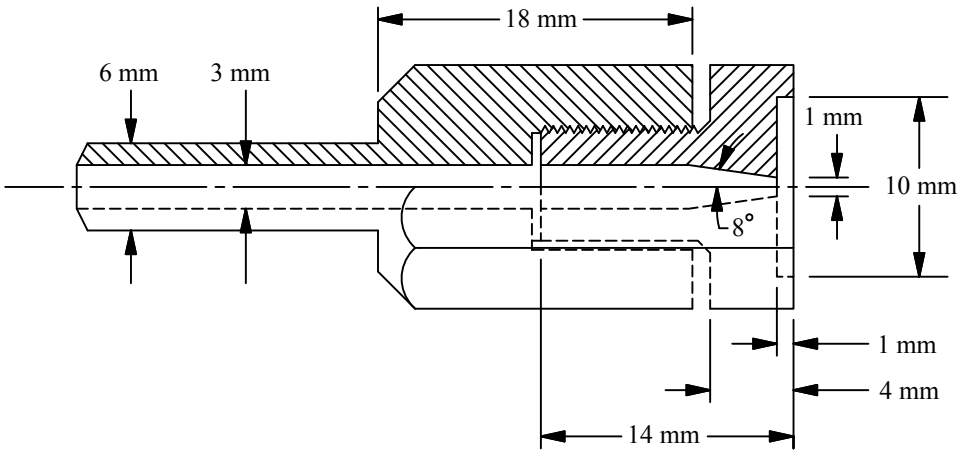
In the case of test objects with a height exceeding 1 m, such measurements should be made near the top, center, and bottom of the object. A similar procedure should be used for test objects with large horizontal dimensions.

The spray apparatus shall be adjusted to produce, within the specified tolerances, precipitation conditions at the test object given in Table 5. Pressure and distance can be varied to achieve the required conditions. Any type and arrangement of nozzles meeting the requirements given in Table 5 may be used. An example of a nozzle that has been found satisfactory in practice is shown in Figure 23, and typical performance data are given in Note 2 after Figure 23. Greater spray distances may be obtained if the nozzles are directed upward at an angle of 15° to 25° from horizontal. Note that if the water pressure is increased above the

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recommended limits, the water jets may break up prematurely and cause an unsatisfactory spray at the test object.



NOTE—Details of orifice only.

Figure 23 — Nozzle

The water temperature and resistivity shall be measured on a sample collected immediately before the water reaches the test object. They may also be measured at other locations (e.g., in a storage reservoir) provided that a check ensures that no significant change occurs by the time the water reaches the test object.

The test object should be pre-wetted for at least 15 minutes. The pre-wetting may be done using unconditioned water. Conditioned water shall meet the requirements of Table 5. The transfer from unconditioned to conditioned water shall be accomplished without interruption of the water flow. This transfer shall be followed by a time interval sufficient to flush all unconditioned water. The conditions listed in Table 5 shall remain within the specified tolerances throughout the remainder of the test.

Unless otherwise specified by a relevant apparatus standard, the test procedure for wet tests should be the same as that specified for the corresponding dry tests. In general, for all alternating and direct voltage wet withstand tests, it is recommended that one flashover should be permitted provided that in a repeat test no further flashover occurs.

NOTE—The length of water jet that can be obtained depends on the diameter of the orifice and on the water pressure. At the optimum pressure, which usually is 3×10^5 Pa to 4×10^5 Pa (3 atm to 4 atm) but which depends on the smoothness of the orifice and the arrangement of the supply pipes, the approximate jet lengths obtainable with the nozzle shown in Figure 23 are 9 m to 11 m.

12. Artificial contamination tests

It should be noted that all contamination tests in this standard apply only to ceramic (porcelain and glass) insulators. Procedures for testing composite insulators should be specified by a relevant apparatus standard. Additional information may be found in IEC 60507 [B114].

Artificial contamination tests are intended to provide information on the behavior of external insulation under conditions representative of contamination in service, although they may not necessarily simulate any

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particular service environment. The effects of natural rain washing on insulators in service shall be taken into consideration in any of the specified procedures.

The following specifications give some general guidance on artificial contamination testing. It is left to the relevant apparatus standards to introduce variations or to give more specific requirements for particular classes of apparatus.

All artificial contamination tests require power supplies with enough capacity to maintain the test voltage at a sufficient level during leakage current discharge activity. The specific requirements for the power supply are given in 12.3 and 12.4 for tests with alternating voltage and direct voltage, respectively.

12.1 Preparation of the test object

Before testing for the first time, the metal parts of the test object and any cement joints may be painted with salt water-resistant paint to assist in preventing corrosion products from contaminating the insulation surfaces during a test.

The test object shall be carefully cleaned before testing for the first time, so that all traces of dirt and grease are removed. Water, preferably heated to 50 °C with the addition of trisodium phosphate or another detergent, shall be used, after which the insulator is to be thoroughly rinsed with tap water. The insulating surfaces can be considered sufficiently clean and free of grease or other contaminating material if large continuous wet areas are observed during wetting. After cleaning, the insulating parts of the test object shall not be touched by hand.

Before each subsequent contamination, the insulator shall be again thoroughly washed with tap water only, to remove all traces of pollution.

Unless otherwise specified by a relevant apparatus standard, the test object, with its metal fittings that are integral parts of it, should be mounted in the test chamber in its in-service orientation. In general, the vertical position is suggested for comparison of different insulator types.

The minimum clearances between any part of the insulator and any grounded object, other than the structure that supports the insulator and the nozzles when used, shall be not less than 0.5 m per 100 kV of test voltage, and, in any case, not less than 1.5 m.

The configuration of the supporting structure, if required, and the energized metal parts, at least within the minimum clearance from the insulator, should reproduce those expected in service as closely as possible.

As regards the influence of capacitive effects on the results, the following considerations can be drawn from the available experience:

a) Fittings are deemed not to affect the results significantly, at least for test voltages up to 450 kV.

b) Internal high capacitance can have some effect on the external surface behavior, particularly in tests with solid layer test methods.

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12.2 General test procedures

12.2.1 Introduction

Contamination tests fall into two categories:

a) The solid layer test method (12.5), in which a fairly uniform layer of a defined solid pollution is deposited on the insulator surface.
b) The salt fog test method (12.6), in which the insulator is subjected to a defined ambient pollution.

Artificial contamination tests involve the application of contamination and the simultaneous or subsequent application of voltage. Only methods in which the test voltage is held constant for at least several minutes are recommended.

Methods in which the voltage is raised gradually to flashover are not proposed for standardization but may be used for special purposes.

A contamination test may be performed to determine one of the following three results:

a) The maximum withstand degree of contamination on the test object at a given test voltage.
b) The maximum withstand voltage at a given degree of contamination on the test object.
c) The 50% withstand voltage at a given degree of contamination on the test object.

12.2.2 Determination of the maximum withstand degree of contamination at a given test voltage

The insulator shall be subjected to a number of tests at a given test voltage and at different degrees of contamination. The tests can be carried out in any sequence provided that:

a) When the total number of individual tests ending in flashover at any degree of contamination reaches two, no further tests shall be carried out at the same or higher degrees of contamination.
b) When the total number of individual tests resulting in withstand reaches three, no further tests shall be carried out at the same or lower degrees of contamination.

Should the individual tests at any degree of contamination lead to three tests resulting in withstand, the degree of contamination used is defined as the maximum withstand degree of contamination at the test voltage, provided that the next higher degree of contamination leads to two individual tests ending in flashover.

12.2.3 Determination of 50% withstand voltage at a given degree of contamination

The insulator shall be subjected to at least 10 “valid” individual tests at a specified degree of contamination. The applied voltage level in each test shall be varied according to the up-and-down method. Each voltage step shall be approximately 5% of the expected 50% withstand voltage.

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The first "valid" individual test shall be selected as being the first one that yields a result different from the preceding ones. Only the individual test and at least nine subsequent individual tests shall be taken as useful tests to be considered to determine the 50% withstand voltage.

The calculation of the 50% withstand voltage (V_{50}) shall be made according to:

$$V_{50} = \frac{\sum_{i=1}^{N} n_i V_i}{N} \tag{43}$$

where

V_i is the applied voltage level

n_i is the number of individual tests carried out at the same applied voltage level V_i

N is the total number of "valid" tests

Alternatively, the method of maximum likelihood (see Clause 15) can be used to obtain V_{50}.

12.3 Power supply requirements for alternating voltage artificial contamination tests

The frequency of the test voltage shall be between 45 Hz and 65 Hz.

In general, the test voltage coincides with the highest line-to-ground voltage the insulator is required to withstand under normal operating conditions.

The power supply has to have a short-circuit current (I_{sc}) higher than in other types of insulator tests. In addition, there are other requirements on the power supply. The minimum value of I_{sc} varies with test conditions as shown below:

$$I_{sc} \geq 6 \quad \text{for} \quad L_s < 16 \tag{44}$$

$$I_{sc} \geq L_s - 10 \quad \text{for} \quad 16 \leq L_s < 25 \tag{45}$$

where

I_{sc} is the short-circuit current in amperes (rms)

L_s is the specific creepage distance (mm/kV$_{\text{line-to-line}}$)

The definition of the specific creepage distance in Equation (44) and Equation (45), namely actual creepage distance divided by the product of line-to-ground voltage and $\sqrt{3}$ (i.e. line-to-line voltage), is consistent with the terminology in IEC 60507.

The requirements for the short-circuit current are given graphically in Figure 24. The available experience is deemed insufficient to give $I_{sc\ \min}$ values for tests at specific creepage distances higher than 25 mm/kV$_{\text{line-to-line}}$.

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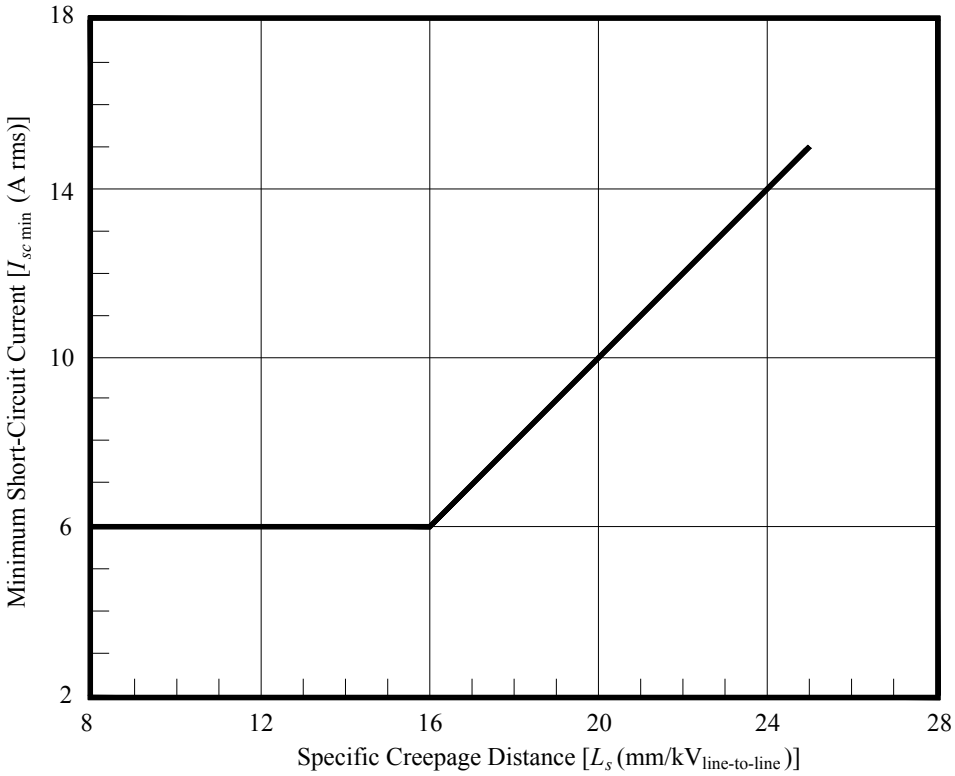


Figure 24 —Minimum short-circuit current versus specific creepage distance for artificial contamination tests

The other requirements related to the power supply are:

a) The reactance/resistance ratio (X/R) shall be less than or equal to 10.

b) The capacitive current/short-circuit current ratio (I_c/I_{sc}) shall be within the range of 0.001 to 0.1.

When the value of I_{sc} of the power supply, although higher than 6 A, does not comply with the limits given in Equation (44) and Equation (45), the verification of a withstand voltage can still be made, provided that the power supply meets the criteria listed below.

In each individual test, the highest leakage current pulse amplitude is recorded and its maximum value ($I_{h\,max}$) determined. The $I_{h\,max}$ values shall comply with:

$$\frac{I_{sc}}{I_{h\,max}} \geq 11 \qquad (46)$$

where

I_{sc} is the short-circuit current in amperes (rms)

I_{hmax} is the highest leakage current pulse amplitude in amperes (peak value)

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12.4 Power supply requirements for direct-voltage artificial contamination tests

The ripple factor of the test voltage shall be less than 3% at a minimum current of 100 mA with a resistive load. Higher values for this minimum current may be specified by a relevant apparatus standard.

The relative voltage drop occurring during individual tests resulting in a withstand shall not exceed 10%.

The relative voltage overshoot, usually due to load-release caused by extinction of electrical discharges on the insulator surface, shall not exceed 10%.

12.5 The solid layer test method

12.5.1 Introduction

The solid layer test method may be performed either with alternating voltage or direct voltage (see [B147] and [B178]).

A contamination layer is applied to the insulator surface using a slurry consisting of water, an inert material such as kaolin, and an appropriate amount of sodium chloride (NaCl) to achieve the required salt deposit density (S_{dd}) or layer conductivity.

12.5.2 Insulator preparation

Prior to conducting the first contamination test, the insulators shall be cleaned by scrubbing the insulation surfaces with an inert material such as kaolin, after which the insulator is to be thoroughly rinsed with clean water. Before every subsequent contamination test, the insulator shall be thoroughly washed again with tap water only.

12.5.3 Contaminant preparation

The kaolin composition consists of:

a) 40 g kaolin

b) 1000 g tap water

c) A suitable amount of NaCl of commercial purity

When the volume conductivity of the water is higher than 0.05 S/m, the use of de-mineralized water is recommended. To achieve the reference degree of contamination on the insulator under test (± 15%), an appropriate value of volume conductivity of the prepared slurry is to be determined by submitting the insulator itself (or part of it) to preliminary contamination trials. The desired volume conductivity is reached by adjusting the amount of salt in the slurry. As a rough guide, Table 6 gives the correspondence between the reference degree of pollution on the insulator and the volume conductivity when the temperature of the slurry is 20 °C (in the case of standard cap and pin insulators contaminated in vertical position at normal ambient conditions). The volume conductivity required for other insulators can vary from the values given in Table 6.

Ranges of values for the main characteristics of inert material, defining the type of kaolin that should be used for the slurry, are given in Table 7.

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Table 6—Kaolin composition: correspondence between the reference degrees of pollution on the insulator and the volume conductivity of the slurry

Salt deposit density S_{dd} (mg/cm^2)	Layer conductivity K_{20} (μS)	Volume conductivity of the slurry σ_{20} (S/m)
0.025	3.0	1.0
0.035	4.2	1.4
0.060	5.5	2.0
0.070	8.0	2.8
0.100	11.0	4.0
0.140	14.5	5.6
0.200	20.0	8.0
0.280	27.0	11.2
0.400	37.0	16.0

NOTE—Volume conductivity for the characterization of inert material is determined with the use of de-mineralized water.

Table 7—Main characteristics of the inert material used in solid layer tests

Type of inert material	Weight composition (%)				Granulometry (cumulative distribution) (μm)			σ_{20} (S/m)
	SiO_2	Al_2O_3	Fe_2O_3	H_2O	16%	50%	85%	
Kaolin	40 to 50	30 to 40	0.3 to 2.0	7 to 14	0.5 to 2	2 to 8	8 to 25	0.0015 to 0.02

NOTE—Granulometry distribution gives the values of the hole diameter of a sieve, in μm, through which one of the quoted percentages of the total mass of particles passes.

12.5.4 Application of the contamination layer

The slurry described in 12.5.3 shall be applied by spraying it or flowing it onto the dry insulator previously cleaned according to 12.5.2, to obtain a reasonably uniform layer. Alternatively, the insulator may be dipped in the slurry, provided its size permits this operation.

The artificial layer may be applied on the insulator surface by spraying the prepared slurry through one or two nozzles of a commercial-type spray gun. The direction of the nozzles shall be adjusted to ensure a reasonably uniform layer on the whole insulator surface. A distance of about 20 cm to 40 cm has been found satisfactory. It is necessary to keep the slurry stirred. The required degree of pollution on the insulator may be obtained by repeated applications.

The coating time can be reduced by preheating the insulator. In this case, the entire insulator should be in thermal equilibrium with the air in the test chamber at the start of the test. The coating time also can be reduced by drying the layer between successive applications.

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Other techniques are suitable and can also be used. For instance, the practice of flooding the prepared slurry over the insulator surface ("flow-on" technique) is particularly suitable for large or long insulators.

Another technique is to apply the contamination by a small paint brush. The surface area of the insulator is measured and the amount of NaCl required to meet the specified S_{dd} (i.e., $S_{dd} \times A$) is accurately measured (by weight). The required amount of NaCl is then mixed with approximately 25 g of kaolin per 5000 cm^2 of surface area. Sufficient water is added to make a thick slurry. About 25 g to 30 g of water per 25 g of kaolin is normally sufficient. All of the mixture is then evenly brushed onto the insulator surface.

NOTE—The above procedure is used in some laboratories as an easier alternative to the spray or dip method as it guarantees the required S_{dd} will be applied to the insulator.

If the uniformity of the layer does not appear to be satisfactory during visual examination, the wet layer conductivity can be checked with a probe and a meter.

A possible arrangement for such a device is described in the following:

- Probe as shown in Figure 25.
  - Two spherical stainless steel electrodes, 5 mm in diameter and having a distance of 14 mm between centers, suspended from the probe, shall be pressed by hand against the insulator surface. A constant surface pressure is obtained by means of a spring mechanism developing a force of approximately 9 N.
- Wet layer conductivity meter as shown in Figure 26.
  - A voltage source stabilized by a Zener-diode at 6.8 V supplies the current across the electrodes and the surfaces between them. The measuring instrument with a full scale deflection at 50 μA is protected by a diode in parallel.
  - For thin films with a layer conductivity of 50 μS, the resistance between the electrodes is assumed to be 32.7 kΩ. The respective values for 100 μS and 500 μS layer conductivity are 16.36 kΩ and 3.27 kΩ. Each of these resistances is combined with a test battery inserted in parallel with the electrodes. The selector switch is used to choose the full scale deflection for the respective measuring ranges.

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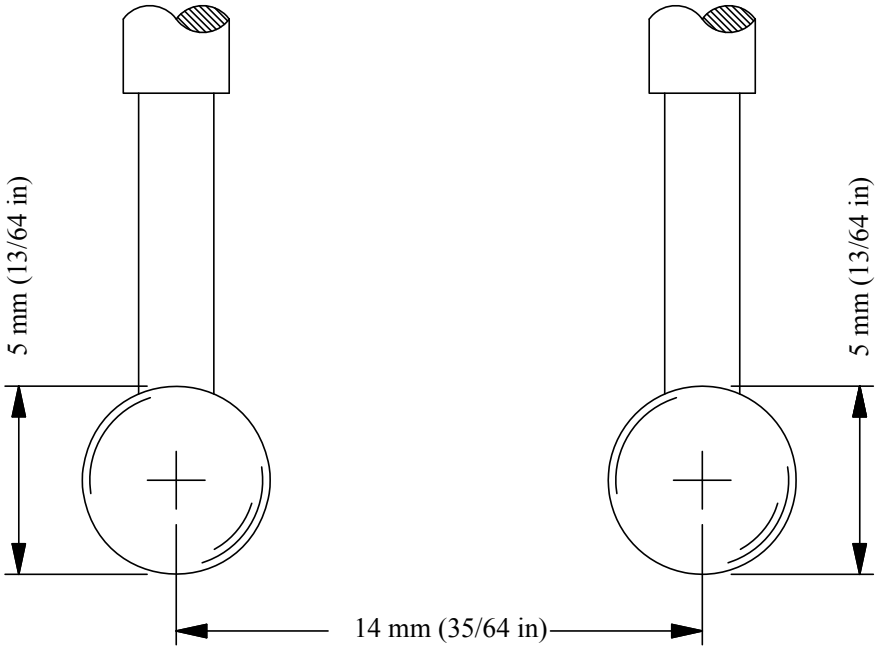


Figure 25 — Arrangement for the probe electrodes

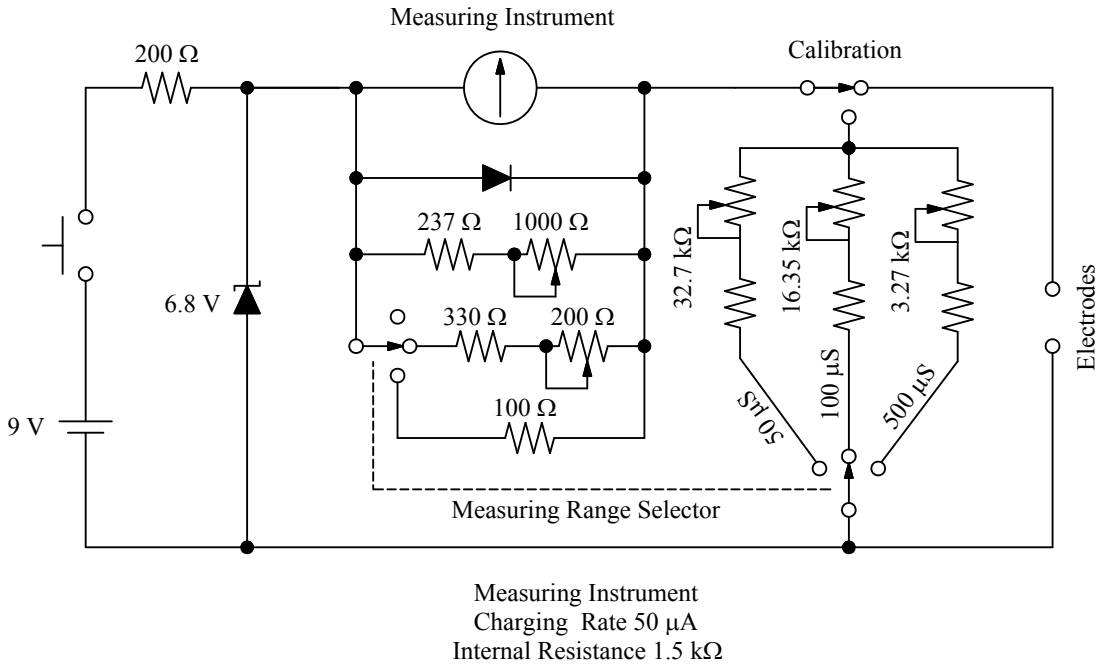


Figure 26 —Circuit diagram of the wet layer conductivity meter

The measurement of layer conductivity shall be carried out at different points of the insulator surface. The polarization effect shall be taken into account by a momentary operation of the meter push-button.

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The uniformity of the layer is deemed acceptable when the difference between each of the measurements and their average, as a percentage of the average value, does not exceed the limits of ± 30 %.

A preconditioning process, as specified for the salt fog test, is not necessary with the solid layer test method. The layer shall be left to dry prior to submission of the insulator to the test. More details are given in the following subclauses.

12.5.5 Determination of the degree of contamination of the tested insulator

The degree of contamination of the tested insulator, expressed in terms of salt deposit density or layer conductivity, is determined from measurements of salt deposit density or layer conductivity.

12.5.5.1 Salt deposit density (S_{dd})

The deposit is removed and carefully collected from the surface of a separate insulator, identical to the tested one (or to a part of it) and contaminated in the same way. The whole surface of this insulator, or upper and lower surfaces separately, are cleaned for this purpose, excluding metal parts and assembly materials.

In the case in which only one cylindrical insulator is available for the test, measurement of salt deposit density is made on a few sheds of it. After that, the cleaned surface has to be repaired by re-applying the contamination layer.

After applying slurry to the insulator (or part of it) chosen for S_{dd} measurement, the drops shall be removed cautiously before drying the layer. This procedure avoids errors in quantifying the degree of contamination that is truly effective in the test.

The deposit is then dissolved in a known quantity of water, preferably de-mineralized water. The resulting slurry is kept stirred for at least 2 minutes before the measurement of its volume conductivity σ_θ (S/m) at the temperature θ (°C). Then the value σ_{20} is obtained from σ_θ by the following relationship:

$$\sigma_{20} = \sigma_\theta \left[1 - b(\theta - 20)\right] \tag{47}$$

where

σ_{20} is the layer conductivity at a temperature of 20 °C (in S/m)
σ_θ is the volume conductivity at a temperature of θ °C (in S/m)
θ is the temperature of the insulator surface (in °C)
b is a factor depending on temperature, as given in the following table:

θ	b
5	0.03156
10	0.02817
20	0.02277
30	0.01905

NOTE—For other values of temperature θ within the range from 5 °C to 30 °C, the factor b can be obtained by interpolation.

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The salinity, S_a (in kg/m^3), of the slurry is determined by the use of the following formula (when σ_{20} is within the range of 0.004 S/m to 0.4 S/m):

$$S_a = (5.7\sigma_{20})^{1.03} \tag{48}$$

The salt deposit density,S_{dd} (in mg/cm^2), is then obtained by the following formula:

$$S_{dd} = \frac{S_a V}{A} \tag{49}$$

where

V is the volume of the slurry (in cm^3)
A is the area of the cleaned surface (in cm^2)

12.5.5.2 Layer conductivity (σ)

The layer conductivity is calculated by multiplying the layer conductance measured on the unenergized insulator by the form factor of the insulator. The form factor is determined from the insulator dimensions and may be estimated graphically by plotting the reciprocal value of the insulator circumference against the partial creepage distance up to the point reckoned; the area under this curve gives the form factor. Mathematically, the form factor is expressed as:

$$F = \int_0^L \left[\frac{1}{p(l)}\right] dl \tag{50}$$

where

F is the form factor
$p(l)$ is the circumference at partial creepage distance l along the surface
L is the total creepage distance
dl is the increment of integration

The layer conductance measurement is repeated on the insulator during its wetting, with the aim of determining the maximum value reached. Each measurement of the layer conductance consists of applying a voltage to the insulator not less than 700 V rms per meter of overall creepage distance, and measuring the current flowing through the wet layer. The voltage shall be applied only long enough to read the meter.

When higher voltage values are used, the measuring time shall be short enough to avoid serious error due to heating or drying of the pollution layer. To this aim, it shall be checked that neither surge activity nor amplitude variations affect the shape of the measured current.

The layer conductivity shall be related to the reference temperature of 20 °C, using the relationship given in Equation (47).

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12.5.6 General requirements for wetting of the pollution layer

The test object shall be wetted by means of fog generators, which provide a uniform fog distribution over the entire length and around the test object. The temperature of the test object at the beginning of the wetting should be within 2 °C of the ambient temperature in the test chamber. A plastic tent surrounding the test object may be used to limit the volume of the test chamber.

The fog generation in the test chamber shall be maintained until the end of the individual test at a constant steady rate of flow.

After a certain degree of wetting of the pollution layer is reached, moisture starts to drip from the edges of insulator sheds. Consequently, some contaminant is removed from the layer, and a progressive washing of the test object can be expected.

The temperature rise in the test chamber, measured at the height of the test object, shall not exceed 15 °C by the end of the test.

12.5.7 Additional recommendations for solid layer test method

The additional recommendations given in the following subclauses go more deeply into the practices of the solid layer test, providing criteria for auxiliary controls during the tests and preventing users not yet sufficiently expert from performing the tests in ways that could lead to possible errors.

12.5.7.1 Contaminating practice

When the spraying or flowing-on practice is used, the operation can be performed on the insulator while it is located in the chamber in its test position. When the dipping practice is used, the insulator shall be contaminated before it is assembled in the test chamber. If the insulator consists of more units in series, each of them shall be dipped separately and then be kept with its axis vertical for the duration of dripping of the contaminant up to the complete drying of the layer.

If, after the contaminating operation, a blotched layer is observed on the insulator, its surface shall be washed and cleaned again according to 12.5.2. Then one or more tentative contaminations shall be performed, each followed by the relevant washing, until a continuous layer is achieved on the insulator. At this time, tests can start on it. Experience has shown that, in general, a few repeated operations are enough to have the insulator surface ready to be contaminated in a satisfactory way without using any preconditioning process.

12.5.7.2 Drying of the pollution layer

Natural drying of the pollution layer on the insulator may be sufficient, provided that it lasts long enough (6 h to 8 h) while the relative humidity around the insulator is kept not higher than 70%. Humidity values lower than this level allow for shorter drying times. If hot air is used to accelerate the drying of the layer, the method for producing hot air shall not result in the deposition of material that affects either the wetting of the insulator surface or the degree of pollution. For instance, some flame combustion methods may generate oil substances that could inhibit the wetting of the insulator surfaces. Finally, the speed of the hot air flow is to be controlled in order to prevent the removal of any content of the layer from the insulator surface.

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12.5.7.3 Check of the wetting action of the fog

In the cases of very low or high outdoor temperature, especially for poor thermal insulation of the chamber, high altitude, or presence of turbulence in the chamber, a direct check could be required of the wetting action of the fog on the test insulator.

A dummy insulator, consisting of a string of at least two units of the standard cap and pin type shown in Figure 27 contaminated at the S_{dd} value equal to 0.07 mg/cm^2, shall be put in the test chamber, in place of the test insulator, at the same average height from the floor. While the fog generation is working as in a real test, the current flowing through the wet layer of the dummy insulator is measured according to the procedure given in 12.5.5.2. The increase of the layer conductance over time shall be monitored and compared with the reference curve given in Figure 27. If necessary, a readjustment of the steady fog rate shall be carried out to ensure that the measured curve matches the reference one.

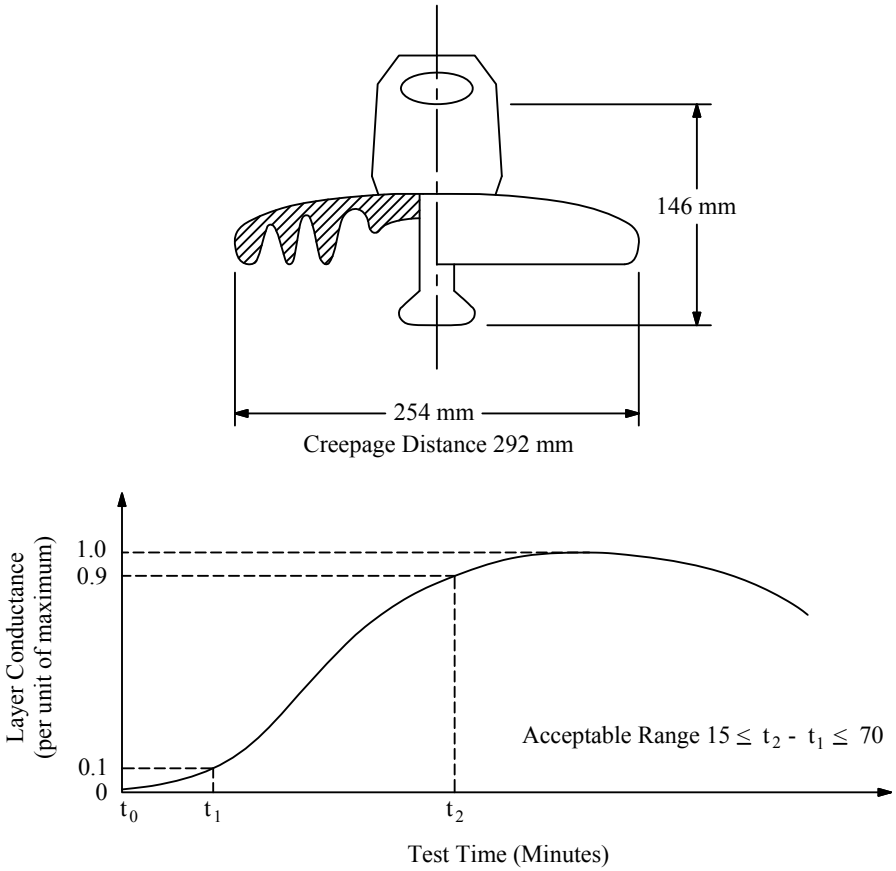


Figure 27 — Control of wetting action of the steam fog: layer conductance recording during the test on the chosen dummy insulator

12.5.7.4 Evaluation of the reference salt deposit density (S_{dd})

The pollution layer shall be removed completely from the chosen area of the insulator. To this effect, at least three consecutive cleanings of that area shall be performed. As a guide, 2 liters to 4 liters of de-mineralized water per square meter of the cleaned surface can be used for dissolving the collected deposit. The effectiveness of the removal operation can be checked by making measurements of the residual deposit.

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Every contaminating practice leads to some difference between the S_{dd} values measured separately on the upper and lower surfaces of the insulator. This difference is affected both by the insulator shape and the type of the slurry. It is suggested to check that the ratio between a local measurement of S_{dd} and that on the entire area of the insulator is in the interval of 0.7 to 1.3.

12.5.8 Test procedures

Two alternative procedures are proposed, basically differing in the layer conditions, dry or wet, of the test object when the test voltage is applied to it. The main rules relevant to the two test procedures are given in the following subclauses.

12.5.8.1 Procedure 1: Wetting after energization

For this procedure, the insulator is contaminated using kaolin composition (see 12.5.3). The degree of contamination is generally expressed in terms of salt deposit density, S_{dd} (see 12.5.5.1).

NOTE—Measurements of the layer conductance are generally not requested. On agreement between the manufacturer and the purchaser, they may be performed during the wetting on a separate, un-energized insulator, identical to the tested one (or to a part of it) and contaminated in the same way.

The insulator is prepared for the test according to 12.5.2 and placed in its test position in the chamber with the contamination layer still dry.

Steam fog shall be used for wetting the layer. The fog is produced by steam that is generated by boiling water in open vats or by steam that is admitted into the test chamber at low velocity through large-diameter nozzles. The fog input to the test chamber shall be allowed only after the steam generation has reached its steady rate. Therefore, when the steam is produced by vats, they have to be kept covered until the water inside reaches the boiling point. The test object shall be positioned so that the visible fog surrounds it as uniformly as possible.

The fog generators shall be under the test object as close as possible to the floor level. In all cases, they shall be at least 1 meter from the test object and their flow shall not be directed towards it.

The steam input rate in the chamber should be zero until the test voltage is applied and constant thereafter. At normal ambient temperature, the steam input rate shall be within the range 0.05 ± 0.01 kg/h per cubic meter of the test chamber volume. In particular, test conditions this value may need some adjustment through a direct check of the wetting action of the fog, as described in Figure 27 and 12.5.7.3.

The test voltage is maintained until flashover occurs. Otherwise, it is maintained for 100 minutes from the start of the test or until the current peaks, if they are measured, have decreased to values permanently lower than 70% of the maximum peak recorded.

For this procedure, the pollution layer is used only once.

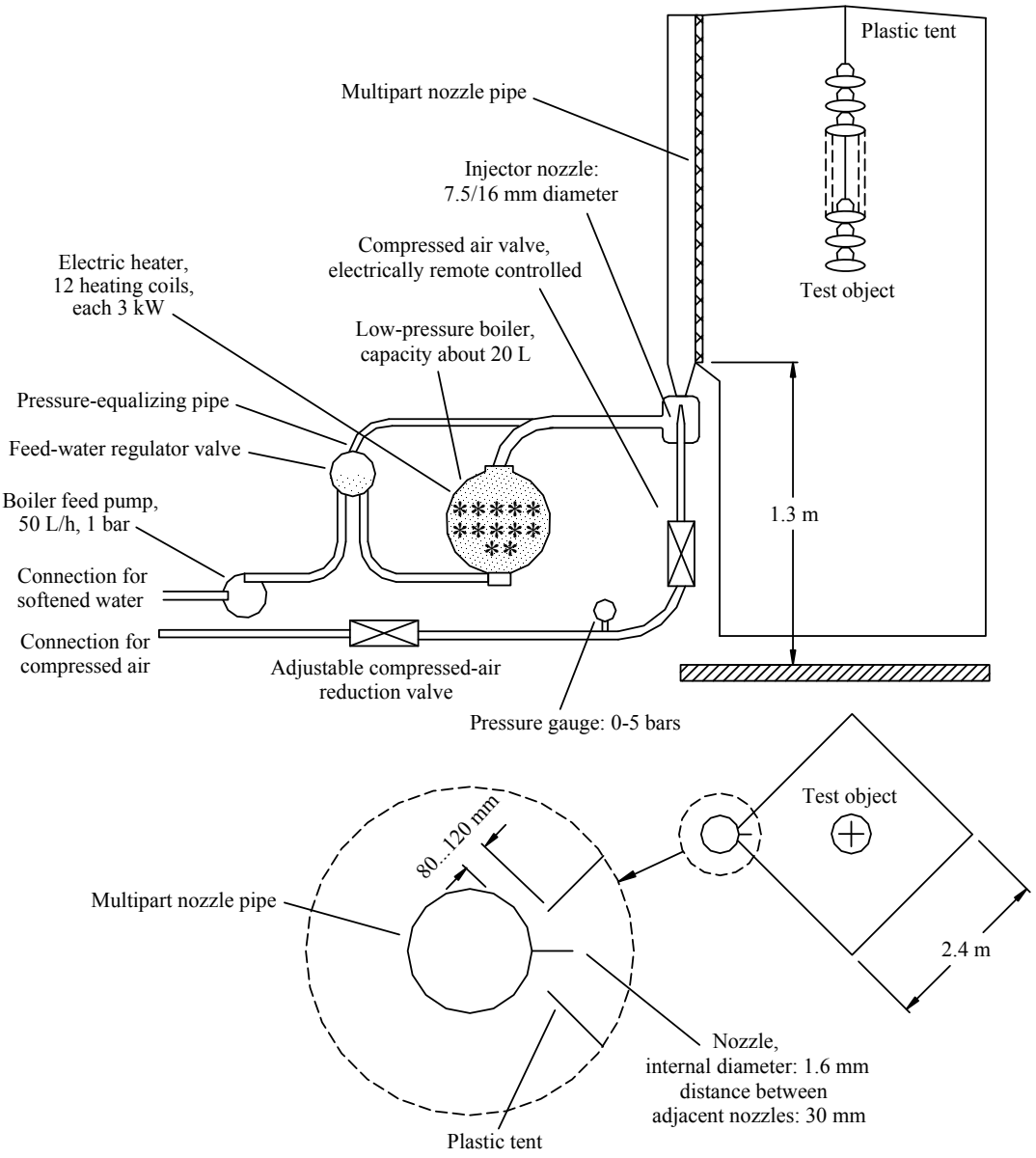
12.5.8.2 Procedure 2: Wetting before and during energization

For this procedure, the insulator is contaminated using kaolin composition. The degree of contamination is generally expressed in terms of layer conductivity, but the salt deposit density S_{dd} may also be used. The insulator is prepared for the test according to 12.5.2 and placed in its test position in the chamber, after which the fog generation is started.

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Preferably, steam fog is used. A steam fog generator, consisting of a distribution pipe with nozzles spaced at equal distance, is shown in Figure 28 as an example.



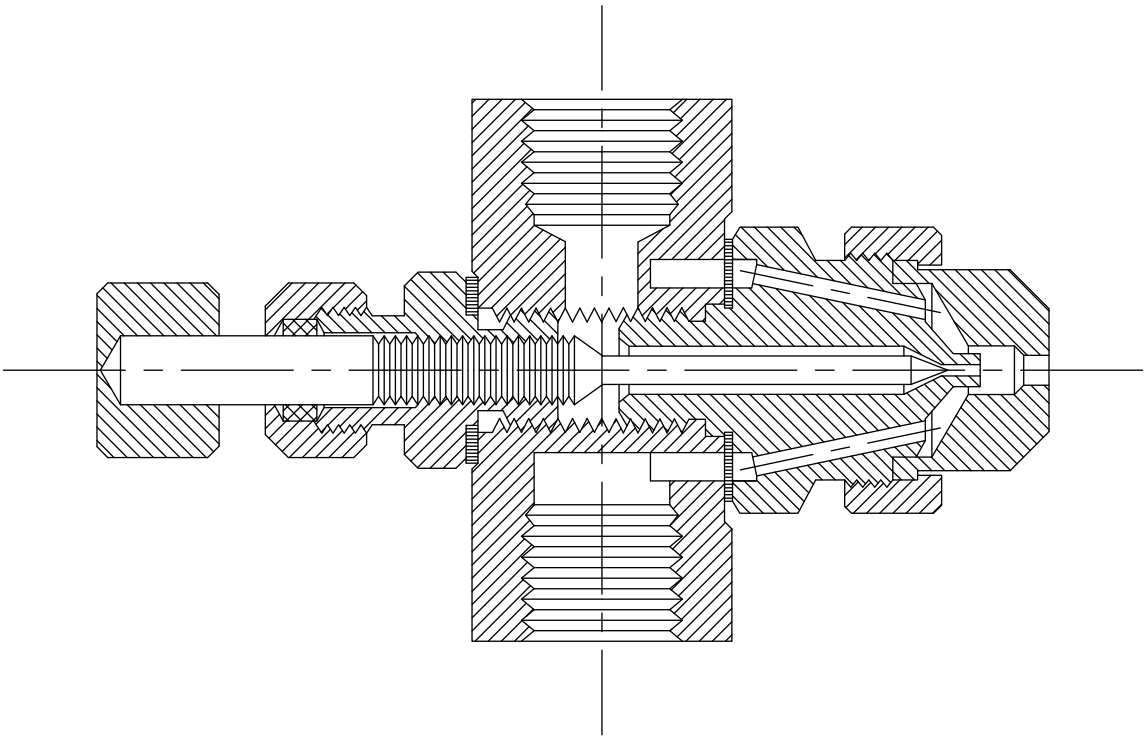
NOTE— Multipart nozzle pipe consists of three nozzle pipes, each 1.5 m in length, and one intermediate pipe without nozzles for elevated installation. Overall total height from the ground: 11 m. Internal diameter of the lower pipe: 120 mm. Internal diameter of the pipes reduced in steps to 50 mm for the upper pipe.

Figure 28 —Typical arrangement of the steam-fog generator

Instead of the steam fog, it is permitted to use a fog generated with nozzles spraying warm or cold water (see as an example of a commercially available nozzle in Figure 29), provided that this fog gives the recommended uniform wetting. When this variant is used, a cooling of the test object may be advantageous before starting the test.

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NOTE—This type of nozzle is commercially available.

Figure 29 —Example of fog nozzle – concentric air and liquid orifices

For the evaluation of the layer conductivity, layer conductivity measurements are performed on the tested insulator according to 12.5.5.2.

The flow rate of the fog input to the chamber, at normal ambient temperature, shall be sufficiently high so that the layer conductivity reaches its maximum value within 20 minutes to 40 minutes from the start of the fog generation. The maximum value of the layer conductivity measured in the test is assumed as reference layer conductivity.

The test voltage is then applied, either instantaneously or over a time not exceeding 5 seconds. The voltage is maintained until flashover, or for 15 minutes if no flashover occurs.

The insulator is then removed from the fog chamber and allowed to dry. It is then placed in the chamber for a second time and re-wetted by the fog until the layer conductivity reaches its maximum value. If the maximum value of layer conductivity is not lower than 90% of the above mentioned reference value, the test voltage is applied again and maintained until flashover, or for 15 minutes if no flashover occurs. No more than two tests can be performed on an insulator with the same contamination layer.

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12.5.8.3 Withstand test and acceptance criterion (common to both Procedures 1 and 2)

The objective of this test is to confirm the specified withstand degree of contamination at the specified test voltage. The insulator complies with this specification if no flashover occurs during three consecutive tests performed in accordance with 12.5.8.1 for Procedure 1 or 12.5.8.2 for Procedure 2.

If only one flashover occurs, a fourth test shall be performed, and the insulator then passes the test if no flashover occurs.

12.6 The salt fog test method

12.6.1 Introduction

The salt fog test may be performed with alternating voltage, but at present, it is not suitable for standardization when used with direct voltage [B147] and [B178]. Check for more current info.

The insulator is subjected to a salt spray that provides an ambient contamination defined by a specified salinity (in kilograms per cubic meter) of the spray water.

The test object is thoroughly wetted with clean tap water. The salt fog system, supplied by water of the prescribed salinity, is started when the test object is still wet and, simultaneously, voltage is applied.

At the start of the test, the insulator shall be in thermal equilibrium with the air in the test chamber. In addition, the ambient temperature shall be not less than 5 °C or greater than 40 °C, and its difference from the temperature of the water solution shall not exceed 15 °C.

Preconditioning of the test object by a number of flashovers during application of salt spray is recommended before the actual tests begin.

12.6.2 Salt solution

The salt solution shall consist of sodium chloride (NaCl) of commercial purity and tap water.

NOTE—Tap water with high hardness (e.g., with a content of equivalent $CaCO_3$ greater than 350 g/m^3) can cause limestone deposits on the insulator surface. In this case, the use of de-ionized water for preparation of the salt solution is recommended. Hardness of tap water is measured in terms of content of equivalent $CaCO_3$, in accordance with the *Condensed Chemical Dictionary* [B55].

The salinity to be used shall be one of the following values: 2.5 kg/m^3 (or 2.5 g/liter), 3.5 kg/m^3, 5 kg/m^3, 7 kg/m^3, 10 kg/m^3, 14 kg/m^3, 20 kg/m^3, 28 kg/m^3, 40 kg/m^3, 56 kg/m^3, 80 kg/m^3, 112 kg/m^3, 160 kg/m^3, or 224 kg/m^3.

The maximum permissible error in salinity is ± 5% of the specified value. It is recommended that the salinity be determined either by measuring the conductivity or by measuring the density with a correction for temperature. The correspondence between the value of salinity, volume conductivity, and density of the solution at a temperature of 20 °C is given in Table 8. When the solution temperature is not at 20 °C, conductivity and density values shall be corrected as described in the following paragraphs.

Care shall be taken that the temperature of salt solution is between 5 °C and 30 °C, since no experience is available to validate tests performed outside of this range of solution temperature.

The conductivity correction for temperature can be made using the relationship given in Equation (51).

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The density correction shall be made using the following formula (valid only for salinities greater than 20 kg/m^3):

$$\delta_{20} = \delta_\theta \left[1 + (200 + 1.3 S_a)(\theta - 20) \times 10^{-6} \right] \quad (51)$$

where

δ_{20} is the density at a temperature of 20 °C (in kg/m^3)
δ_θ is the density at a temperature of θ °C (in kg/m^3)
S_a is the salinity (in kg/m^3)
θ is the solution temperature (in °C)

Table 8—Salt-fog method: correspondence between the value of salinity, volume conductivity, and density of the solution at a temperature of 20 °C

Salinity S_a (kg/m^3)	Volume conductivity σ_{20} (S/m)	Density δ_{20} (kg/m^3)
2.5	0.43	–
3.5	0.60	–
5	0.83	–
7	1.15	–
10	1.6	–
14	2.2	–
20	3.0	–
28	4.1	1018.0
40	5.6	1025.9
56	7.6	1037.3
80	10.0	1052.7
112	13	1074.6
160	17	1104.5
224	20	1140.0

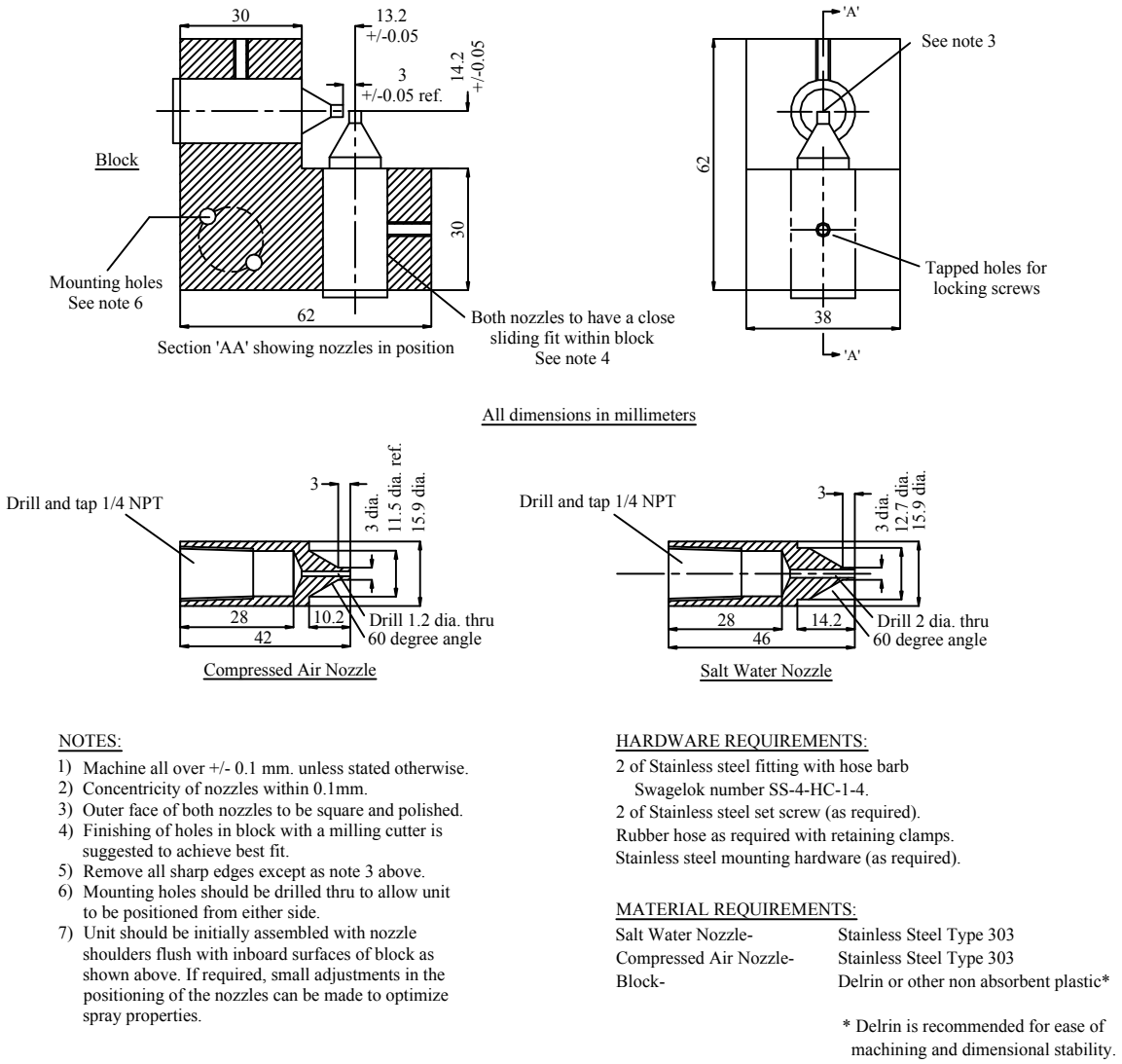
12.6.3 Nozzle system

The fog is produced in the test chamber by means of the specified number of nozzles that atomize the solution by a stream of compressed air flowing at right angles to the solution nozzle. The nozzles consist of corrosion-resistant tubes, the internal diameter of the air nozzles being 1.2 mm ± 0.02 mm and the internal diameter of the solution nozzles being 2.0 mm ± 0.02 mm. Both nozzles shall have an outside diameter of 3.0 mm ± 0.05 mm, and the ends of the nozzles shall be square cut and polished.

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The end of the solution nozzle shall lie on the axis of the air nozzle to within ± 0.05 mm. The distance between the end of the compressed air nozzle and the central line of the solution nozzle shall be 3.0 mm ± 0.05 mm. The axes of the two nozzles shall lie in the same plane to within ± 0.05 mm. A typical construction of the fog nozzle is shown in Figure 30.



NOTES:

1) Machine all over +/- 0.1 mm. unless stated otherwise.
2) Concentricity of nozzles within 0.1mm.
3) Outer face of both nozzles to be square and polished.
4) Finishing of holes in block with a milling cutter is suggested to achieve best fit.
5) Remove all sharp edges except as note 3 above.
6) Mounting holes should be drilled thru to allow unit to be positioned from either side.
7) Unit should be initially assembled with nozzle shoulders flush with inboard surfaces of block as shown above. If required, small adjustments in the positioning of the nozzles can be made to optimize spray properties.

HARDWARE REQUIREMENTS:

2 of Stainless steel fitting with hose barb
Swagelok number SS-4-HC-1-4.
2 of Stainless steel set screw (as required).
Rubber hose as required with retaining clamps.
Stainless steel mounting hardware (as required).

MATERIAL REQUIREMENTS:

Salt Water Nozzle-	Stainless Steel Type 303
Compressed Air Nozzle-	Stainless Steel Type 303
Block-	Delrin or other non absorbent plastic*

* Delrin is recommended for ease of machining and dimensional stability.

Figure 30 —Nozzle used for the salt fog test

The nozzles shall be in two columns parallel to and on opposite sides of the insulator, which shall have its axis in the same plane as the columns. That is, a vertical insulator will be tested with vertical columns and a horizontal insulator with horizontal columns. In the case of an inclined insulator, as shown in Figure 31, the plane containing the insulator and the columns shall intersect the horizontal plane in a line at right angles to the insulator axis; in this case, the axis of the solution nozzles is vertical. The distance between the solution nozzles and the insulator axis shall be 3.0 m ± 0.05 m.

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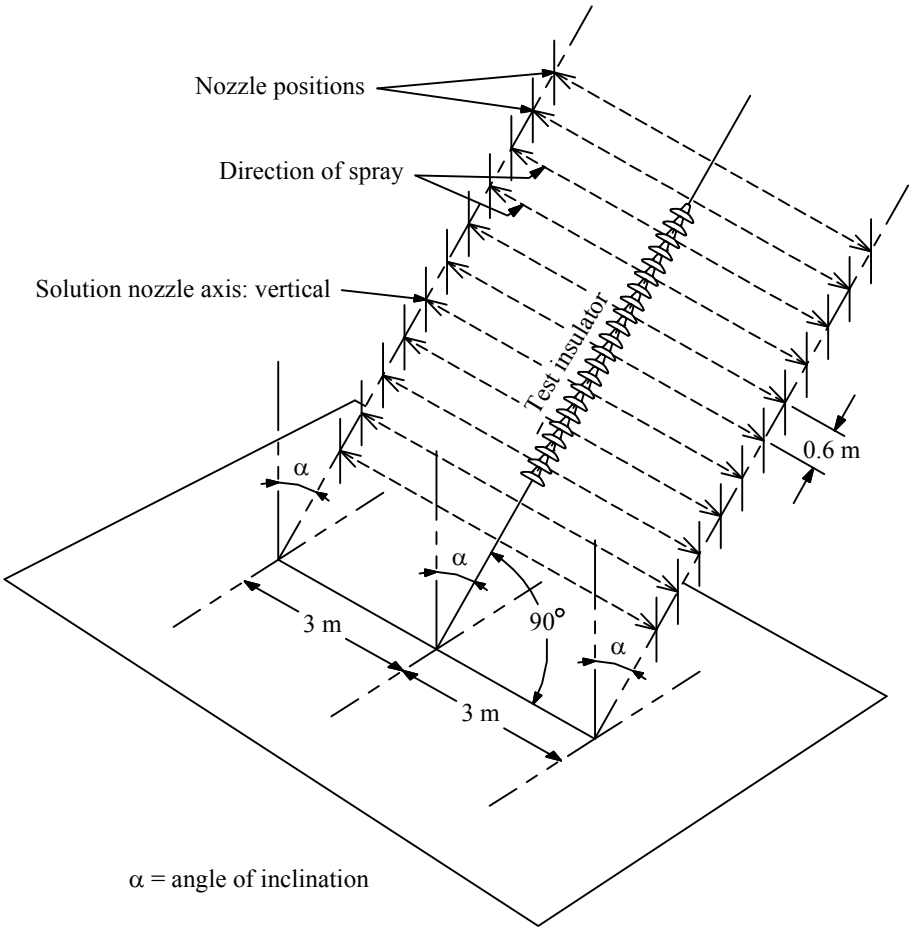


Figure 31 —Test layout for inclined insulators

The nozzles shall be spaced at 0.6 m intervals, each nozzle pointing at right angles to the column axis towards its counterpart on the other column and within an angle of 1° to the plane of the nozzles. This alignment can be checked for vertical nozzles by lowering the solution nozzle, passing water through the air nozzle and directing it towards the opposing nozzle and, afterwards, raising the solution nozzle to the operating position. The midpoint of the insulator shall be preferably in line with the midpoints of the columns of nozzles. Both columns shall extend beyond the insulator at both ends by at least 0.6 m.

NOTE—Conductivity units that can be used are: 1 S/m = 0.01 S/cm = 10 mS/cm = 10 000 μS/cm

The minimum number of nozzles per column shall be:

$$N = \frac{H}{0.6} + 3 \tag{52}$$

where

N is the number of nozzles per column
H is the length of the insulator (in m)

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The nozzles shall be supplied with filtered, oil-free air at a relative pressure of $(7.0 \pm 0.35) \times 10^5$ Pa. The flow of solution to each nozzle shall be 0.5 L/min ± 0.05 L/min for the period of the test, and the tolerance on the total flow to all nozzles shall be ± 5% of the nominal value.

12.6.4 Conditions before starting the test

The test shall start while the insulator, cleaned according to 12.5.2, is still completely wet. At the start of the test, the insulator shall be in thermal equilibrium with the air in the test chamber. In addition, the ambient temperature shall be not less than 5 °C or greater than 40 °C and its difference from the temperature of the water solution shall not exceed 15 °C.

The insulator is energized, the salt-solution pump and air compressor are switched on, and the test is deemed to have started as soon as the compressed air has reached the normal operating pressure at the nozzles.

12.6.5 Preconditioning process

The insulator, prepared in the normal way, is subjected to the test voltage at the reference salinity for 20 minutes or until the insulator flashes over; if the insulator does not flash over, the voltage is raised in steps of 10% of the test voltage every 5 minutes until flashover.

After flashover, the voltage is reapplied and raised as quickly as possible to 90% of the previously obtained flashover voltage and thereafter increased in steps of 5% of the flashover voltage every 5 minutes until flashover. The last process is repeated six more times; in each of them, the voltage is raised rapidly to 90% of the last obtained flashover voltage and then in steps of 5% every 5 minutes until flashover. After eight flashovers, the fog shall be cleared, the insulator shall be washed with tap water, and then the withstand test (see 12.6.6.1) shall start as soon as possible afterwards.

The characteristics of the voltage source used in the preconditioning process are to be not lower than the reference ones in the withstand test (see 12.3 and 12.4).

If the preconditioning process performed at the reference salinity requires excessively high voltages, the use of higher values of salinity is permitted for the preconditioning. Also, if even with this expedient the required voltage remains excessively high, separate preconditionings of shorter sections of the insulator, using adequate procedures to avoid over-stressing of the internal insulation, if any (e.g., in the case of arresters or bushings), are permitted.

12.6.6 Test procedure

12.6.6.1 Withstand test

The objective of this test is to confirm the specified withstand salinity of the insulator at the specified test voltage. The test shall start when the test insulator and the chamber conditions fulfill the requirements given in 12.6.4 and after the preconditioning of the insulator according to 12.6.5.

A series of tests are performed on the insulator at the specified test voltage, using a salt solution having the specified test salinity that shall be in accordance with 12.6.2. The duration of each test shall be 1 hour if no flashover occurs before that time has elapsed. The insulator shall be carefully washed with tap water before each subsequent test.

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12.6.6.2 Acceptance criterion for the withstand test

The insulator complies with this standard if no flashover occurs during a series of three consecutive tests in accordance to the procedure in 12.6.6.1. If only one flashover occurs, a fourth test shall be performed and the insulator then passes the test if no flashover occurs.

If four individual tests result in withstands at, for example, 224 kg/m^3 salinity, the maximum withstand salinity shall be assumed to be equal or greater than 224 kg/m^3. If one individual test ends in flashover and three individual tests result in withstands at 224 kg/m^3 salinity, this salinity shall be considered as the maximum withstand salinity.

13. Atmospheric corrections

13.1 Atmospheric conditions

The standard reference atmosphere is:

a) Temperature $t_0 = 20$ °C

b) Pressure $b_0 = 101.3$ kPa (1013 mbar)

c) Absolute humidity $h_0 = 11$ g/m^3

A pressure of 101.3 kPa corresponds to the height of 760 mm in a mercury barometer at 0 °C. The atmospheric pressure in kilopascals is approximately:

$$b = 0.1333H \tag{53}$$

where

b is the barometric pressure (in kPa)

H is the barometric height (in mm of mercury)

Correction for temperature is considered to be negligible with respect to the height of the mercury column.

13.2 Atmospheric correction factors

The disruptive discharge of external insulation depends upon the atmospheric conditions. Usually, the disruptive discharge voltage for a given path in air is increased by an increase in either air density or humidity. However, when the relative humidity exceeds about 80%, the disruptive discharge voltage becomes irregular, especially when the disruptive discharge occurs over an insulating surface.

By applying correction factors, a disruptive discharge voltage measured in given test conditions (temperature t, pressure b, humidity h) may be converted to the value that would have been obtained under the standard reference atmospheric conditions (t_0, b_0, h_0). Conversely, a test voltage specified for given reference conditions can be converted into the equivalent value under the test conditions.

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Two methods have been widely used for correction of test voltages due to atmospheric conditions:

a) *Method 1:* Atmospheric corrections using factor K (recommended method for new equipment).
b) *Method 2:* Atmospheric correction using factors k_d and k_h (alternate method for air gaps < 1 m and comparisons against historic data).

NOTE—Method 1, above, is a more recent method and is a more internationally accepted method of correcting voltages. However, Method 2, above, has been a common method for historical testing and has value for tests on existing equipment designs.

13.2.1 Atmospheric corrections using Method 1

The disruptive discharge voltage is proportional to the atmospheric correction factor, K, defined by Equation (54):

$$K = k_1 k_2 \tag{54}$$

where

k_1 is the air density correction factor given in 13.2.1.1

k_2 is the humidity correction factor given in 13.2.1.2

If not otherwise specified by the relevant apparatus standard, the voltage, V, to be applied during a test on external insulation is determined by:

$$V = V_0 K \tag{55}$$

where

V_0 is the voltage at standard reference atmosphere

Similarly, measured disruptive discharge voltages, V, are corrected to V_0 corresponding to standard reference atmosphere by dividing by K:

$$V_0 = \frac{V}{K} \tag{56}$$

The test report shall always contain the actual atmospheric conditions during the test and the correction factors applied.

13.2.1.1 Air density correction factor (k_1)

The air density correction factor, k_1, depends on the relative air density, δ, and can be generally expressed as:

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$$k_1 = \delta^m \tag{57}$$

where

m is an exponent defined in 13.2.1.3

When the temperatures t and t_0 are expressed in degrees Celsius and the atmospheric pressures b and b_0 are expressed in the same units (kilopascals or millibars), the relative air density is:

$$\delta = \left(\frac{b}{b_0}\right)\left(\frac{273+t_0}{273+t}\right) \tag{58}$$

The correction is considered reliable for $0.8 < k_1 < 1.05$.

13.2.1.2 Humidity correction factor (k_2)

The humidity correction factor may be expressed as:

$$k_2 = k^w \tag{59}$$

where

w is an exponent defined in 13.2.1.3

k is a parameter that depends on the type of test voltage and may be obtained as a function of the ratio of absolute humidity, h, to the relative air density, δ, using the following equations (see Figure 32):

Direct voltage:

$$k = 1 + 0.014(h/\delta - 11) - 0.00022(h/\delta - 11)^2 \qquad \text{for } 1\ \text{g/m}^3 < h/\delta < 15\ \text{g/m}^3 \tag{60}$$

Alternating voltage:

$$k = 1 + 0.012(h/\delta - 11) \qquad \text{for } 1\ \text{g/m}^3 < h/\delta < 15\ \text{g/m}^3 \tag{61}$$

Impulse voltage:

$$k = 1 + 0.010(h/\delta - 11) \qquad \text{for } 1\ \text{g/m}^3 < h/\delta < 20\ \text{g/m}^3 \tag{62}$$

NOTE—The impulse equation is based on experimental results for positive lightning impulse waveforms. This equation also applies to negative lightning impulse and switching impulse voltages.

For system voltages below 72.5 kV (or approximately gap lengths $l < 0.5$ m), no humidity correction shall be applied (i.e., w = 0).

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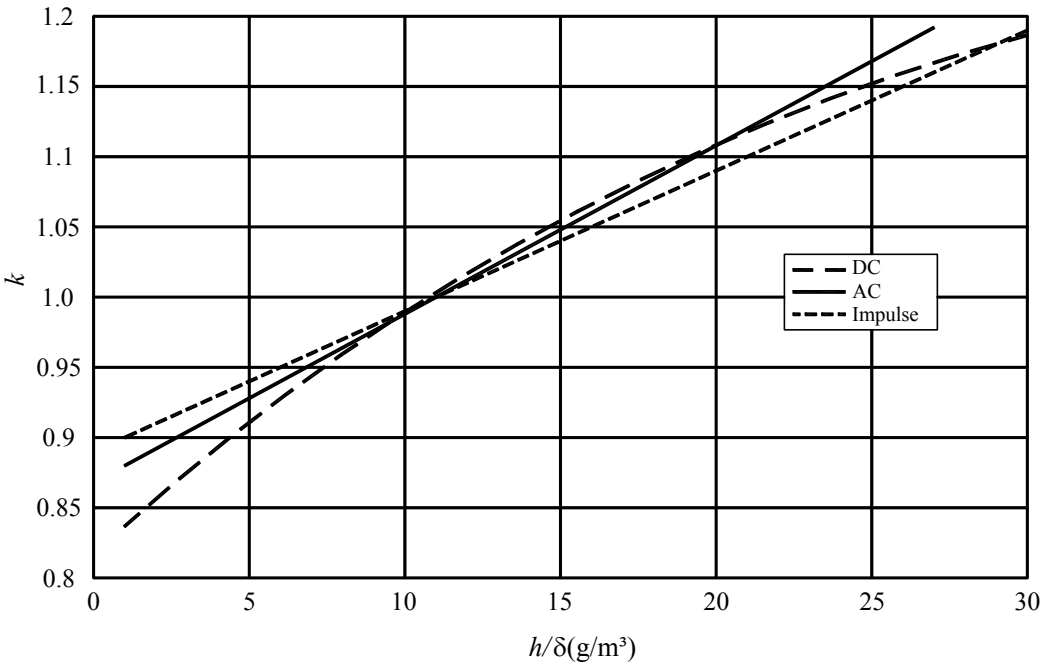


Figure 32 —Parameter *k* as a function of *h/δ*

13.2.1.3 Exponents *m* and *w*

Since the correction factors depend on the type of pre-discharges, this fact can be taken into account by considering the parameter g defined in Equation (63).

$$g = \frac{V_B}{500 L \delta k} \tag{63}$$

where

V_B is the (measured or estimated) 50% disruptive discharge voltage at the actual atmospheric conditions (in kV peak). In the case of a withstand test where an estimate of the 50% disruptive discharge voltage is not available, V_B can be assumed to be 1.1 times the test voltage.

L is the minimum discharge path (in meters).

δ is the relative air density.

k is the dimensionless parameter defined in 13.2.1.2.

The exponents m and w are obtained from Table 9 for the specified values of g, and are plotted in Figure 33 and Figure 34.

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Table 9—Values of exponents *m* for air density correction and *w* for humidity correction as a function of the parameter *g*

g	*m*	*w*
< 0.2	0	0
0.2 to 1.0	$g(g - 0.2) / 0.8$	$g(g - 0.2) / 0.8$
1.0 to 1.2	1.0	1.0
1.2 to 2.0	1.0	$(2.2 - g)(2.0 - g) / 0.8$
> 2.0	1.0	0

NOTE—The values of exponents *m* and *w* have been deduced from experimental values obtained in different conditions, however these are limited to altitudes between sea level and 2000 m. Values for use above 2000 m are under consideration, especially for ac and switching impulse voltages. In the absence of specifications for altitude correction above 2000 m by the relevant apparatus standard, the correction factors in this standard should be used. Significant differences in the correction factors may arise at stresses close to breakdown.

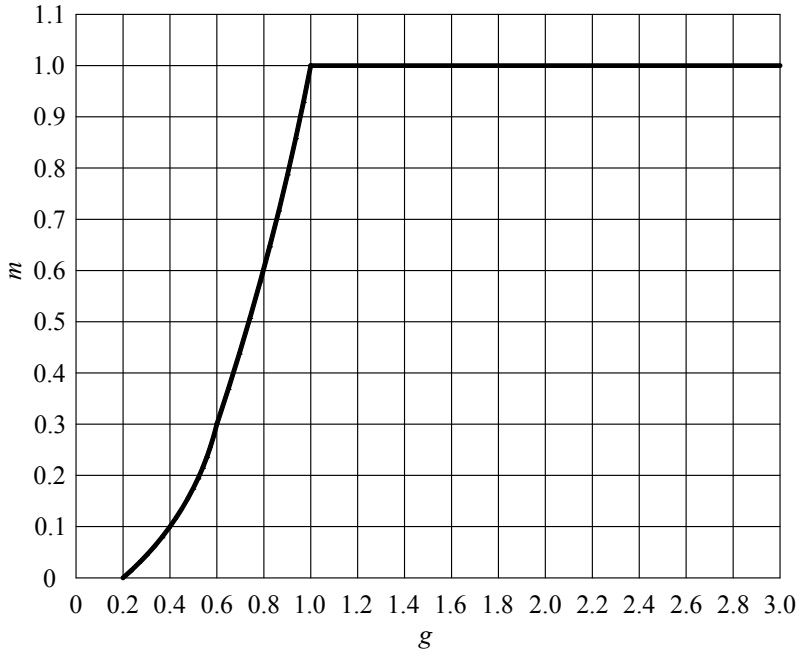


Figure 33 —Value of exponent *m* for air density correction as a function of the parameter *g*

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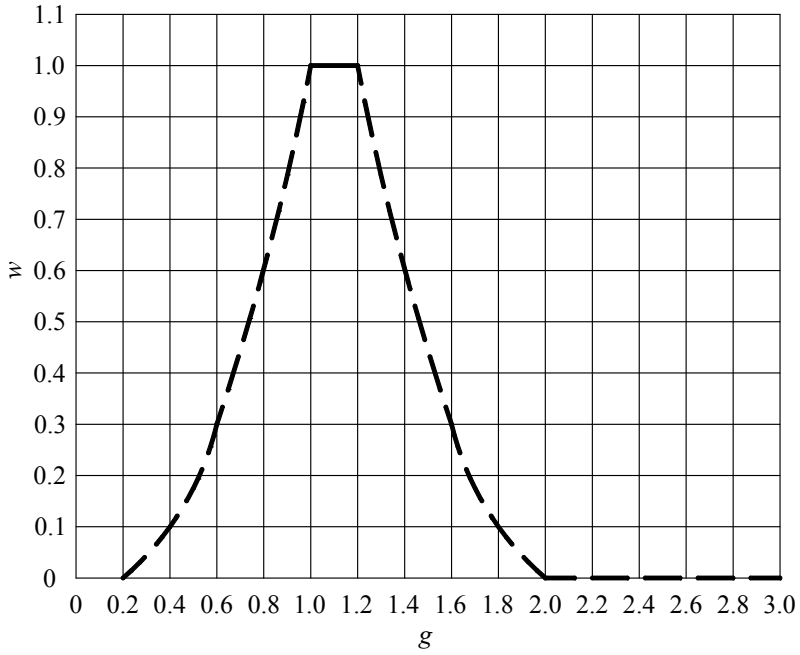


Figure 34 — Value of exponent w for air density correction as a function of the parameter g

13.2.1.4 Wet tests, tests under artificial contamination, and combined tests

No humidity correction shall be applied for wet tests or for tests with artificial pollution. The question of density correction during such tests is under consideration. For combined tests, the atmospheric correction factors relative to the component of highest value shall be applied to the test voltage value.

13.2.2 Atmospheric correction using Method 2

There are two factors:

a) The air density correction factor k_d (see 13.2.2.1)

b) The humidity correction factor k_h (see 13.2.2.1)

The disruptive discharge voltage is proportional to k_d/k_h.

If not otherwise specified by the relevant apparatus standard, the voltage to be applied during a withstand test on external insulation is determined by multiplying the specified withstand voltage by k_d/k_h. Similarly, measured disruptive discharge voltages are corrected to those applicable for standard reference atmosphere by dividing by k_d/k_h.

It is left to the relevant apparatus standard to specify whether or not corrections have to be applied to the voltage values in those cases in which both external and internal insulations are involved. The test report should always contain the actual atmospheric conditions during the test and it must be indicated whether corrections have been applied or not.

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13.2.2.1 Air density and humidity correction factors

The air density correction factor, k_d, is given by:

$$k_d = \left(\frac{p}{p_0}\right)^m \times \left(\frac{273 + t_0}{273 + t}\right)^n \quad (64)$$

where

p is the atmospheric pressure under test conditions

t is the temperature in °C under test conditions

Similarly, the humidity correction factor is given by:

$$k_h = k^w \quad (65)$$

The constant k is given in Figure 35 as a function of absolute humidity, Curve a or Curve b being applicable according to the type of voltage. The exponents m, n, and w depend on the type and polarity of voltage and on the flashover distance d as given in Table 10 and Figure 36. Lacking more precise information, m and n are assumed to be equal.

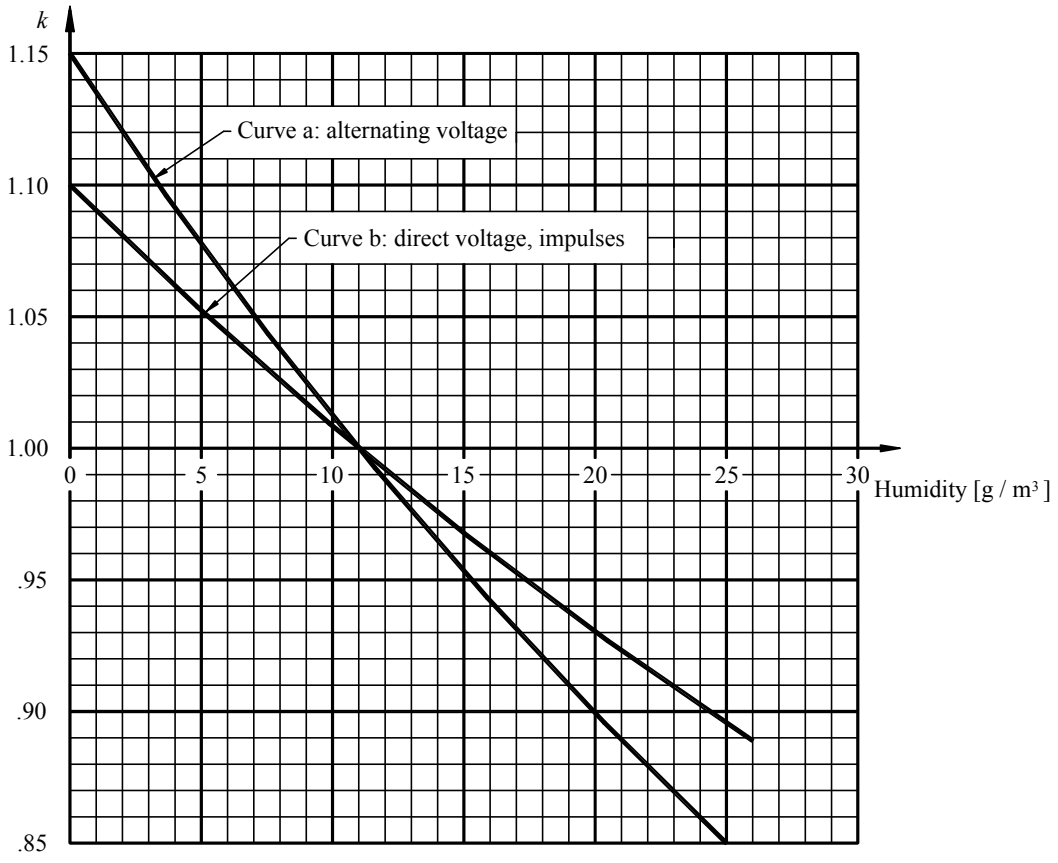
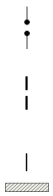
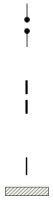


Figure 35 —Humidity correction factor k as a function of absolute humidity

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Table 10—Application of atmospheric correction factors

Type of test voltage	Electrode form	Polarity	Air density correction exponents *m* and *n* (see Note 2)	Humidity correction	
				Factor *k*	Exponent *w*
Direct voltage		+	1.0	See Figure 35 (Curve b)	0
		–			0
		+			1.0
		–			1.0
		+			1.0
		–			0
Alternating voltage		~	1.0	See Figure 35 (Curve a)	0
		~	See Figure 36		See Figure 36
		~	See Figure 36		See Figure 36
Lightning impulse voltage		+	1.0	See Figure 35 (Curve b)	0
		–			0
		+			1.0
		–			0.8
		+			1.0
		–			0
Switching impulse voltage		+	1.0	See Figure 35 (Curve b)	0
		–	1.0		0
		+	See Figure 36		See Figure 36
		–	0 (see Note 1)		0 (see Note 1)
		+	See Figure 36		See Figure 36
		–	0 (see Note 1)		0 (see Note 1)

The electrodes in Table 10 are:

Gaps giving an essentially uniform field.

Rod-rod gaps and test objects with electrodes giving a non-uniform field, but with essentially symmetrical voltage distribution.



Rod-plane gaps and test objects with similar characteristics such as support insulators; that is, electrodes giving a non-uniform field with a pronounced asymmetrical voltage distribution.

For any electrode arrangement not falling into one of the preceding classes, only the air density correction factor, using exponents $m = n = 1$, and no humidity correction, should be applied.

For wet tests, the air density correction factor should be applied but not the humidity correction factor. For artificial contamination tests neither correction factor should be used.

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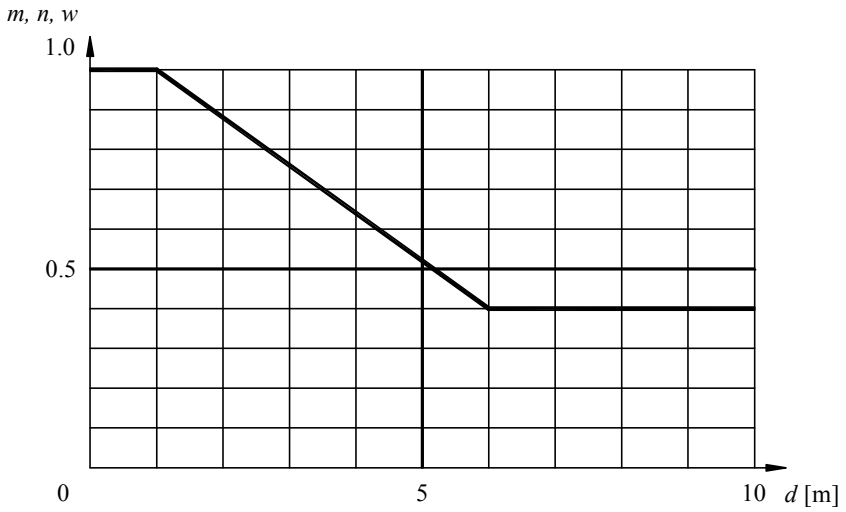


Figure 36 —Value of the exponents *m* and *n* for air density correction and *w* for humidity corrections, as a function of sparkover distance *d*, in meters

NOTE 1—Very little information is available. At present no correction is recommended.

NOTE 2—In Figure 35 and Figure 36 and Table 11, a simplification of the existing information is given. The available experimental data from different sources always show large dispersions and are often conflicting; moreover, relevant information for direct voltages and for switching impulses is scarce. The correctness of using equal exponents *m* and *n*, and of their numerical values as given, is therefore uncertain.

13.3 Measurement of atmospheric parameters

13.3.1 Humidity

The humidity shall preferably be determined with a meter directly measuring the absolute humidity, with an uncertainty not larger than 1 g/m^3. Measurement of relative humidity and the ambient temperature can also be used for the determination of the absolute humidity, provided that the accuracy of the absolute humidity determination is the same as required above.

The measurement of absolute humidity may also be made by means of a hygrometer consisting of two ventilated accurate thermometers, one being dry, and the other wetted. The absolute humidity as a function of the two thermometer readings is determined by Figure 37, which also permits a determination of the relative humidity. It is important to provide adequate air flow (4 m/s to 10 m/s) to reach steady-state values of the readings and to read the thermometers carefully, in order to avoid excessive errors in the determination of humidity.

Other methods for the determination of the humidity are available and may be used if it can be demonstrated that they are sufficiently accurate.

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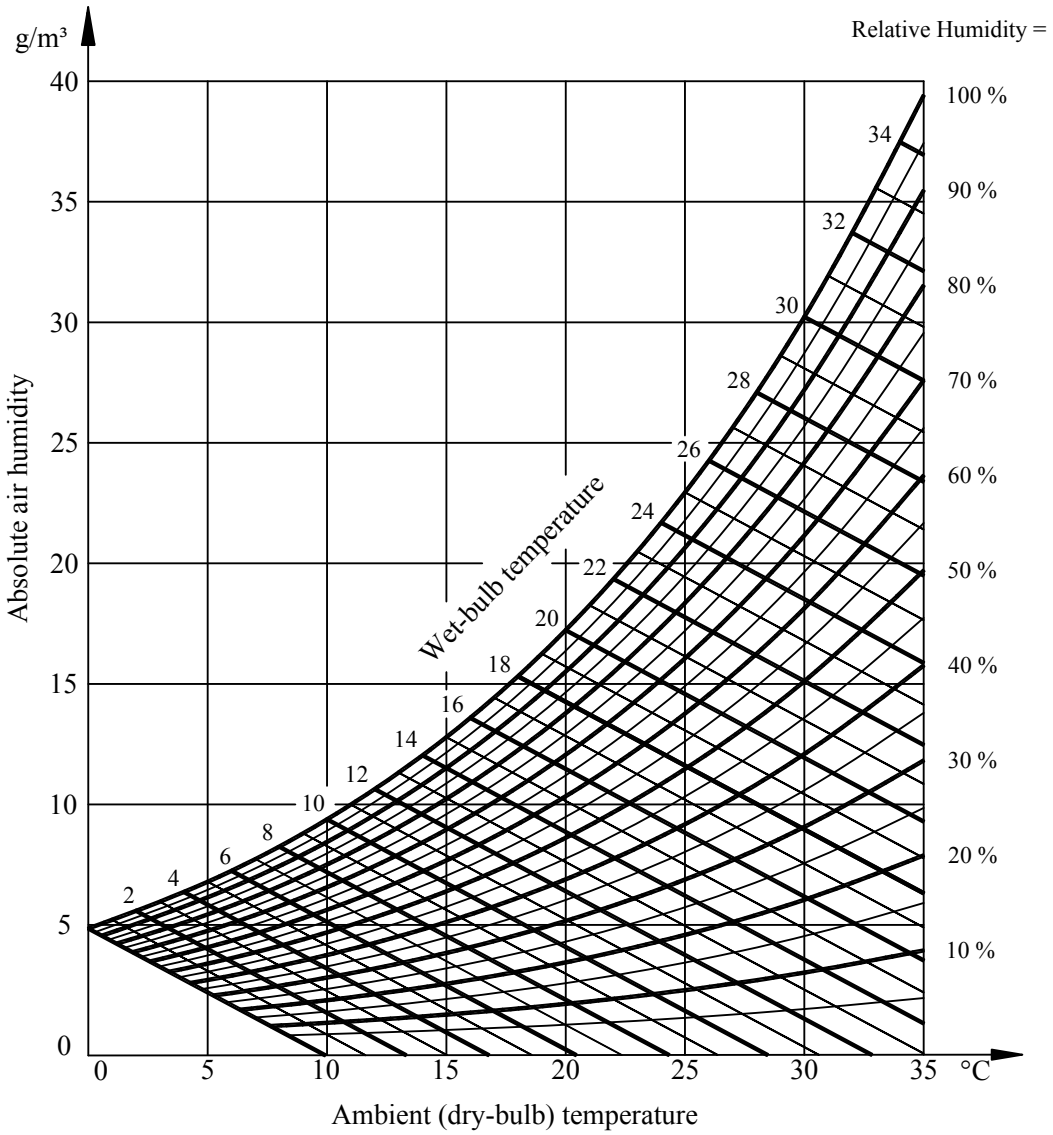


Figure 37 —Absolute humidity of air as a function of dry- and wet-bulb thermometer readings (standard pressure only)

13.3.2 Temperature

The ambient temperature should be measured with an expanded uncertainty of not larger than 1°C.

13.3.3 Absolute pressure

The ambient absolute pressure should be measured with an expanded uncertainty of not larger than 0.2 kPa.

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13.4 Conflicting requirements for testing internal and external insulation

While withstand levels are specified under standard atmospheric conditions, cases will arise in which the application of atmospheric corrections (due to laboratory altitude or to extreme climatic conditions) results in the withstand level for internal insulation appreciably in excess of that for the associated external insulation. In such cases, measures to enhance the withstand level of the external insulation shall be adopted in order to permit application of the correct test voltage to the internal insulation. These measures include immersion of the external insulation in liquids or compressed gasses and should be specified by the relevant apparatus committee with reference to the requirements of particular classes of apparatus. In those cases in which the test voltage of the external insulation is higher than that of the internal insulation, the external insulation can only be correctly tested when the internal insulation is over designed. If not, the internal insulation should be tested with the rated value and the external insulation should be tested by means of test fixtures unless the relevant apparatus committee states otherwise, in which case they shall specify the test procedure to be used.

It is left to the relevant apparatus standard to specify whether or not corrections have to be applied to the voltage values in those cases in which both external and internal insulations are involved.

14. Voltage measurement by means of sphere gaps and rod gaps

14.1 Terms associated with sphere and rod gap voltage measurements

spark-gap: A device with two or more electrodes designed for sparkover to occur under specified and predictable conditions

14.2 General information on spark-gaps

14.2.1 Voltage measurements

A measurement of voltage by means of a spark-gap consists of establishing the relation between a voltage in the test circuit, as calculated by the techniques described in this clause, and the indication of a voltmeter in the control circuit. In essence, the peak value of the voltage obtained from a suitable measuring or recording device connected to the low-voltage side of a measuring system is measured by the spark-gap. Unless the contrary can be shown, the relation established ceases to be valid if the circuit is altered in any respect other than due to a change of the spacing of the electrodes.

Since the voltage at which the spark-gap sparks over is calculated from the spacing between the electrodes and certain other physical parameters of the equipment, the gap shall be measured by a method consistent with the overall uncertainty of the voltage measurement.

Sphere gaps are not recommended for the measurement of direct voltages because of the erratic behavior of these gaps due to particles in the air. These particles cause disruptive discharges at voltages lower than those calculated from the dimensions. Instead, the rod-rod gap is recommended for the measurement of direct voltage, provided the humidity range is between 1 g/m^3 to 13 g/m^3.

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14.2.2 Standard sphere gap

The standard sphere gap is a peak voltage measuring device constructed and arranged in accordance with this standard. The locations on the two spheres that are closest to each other are called the sparking points. Figure 38 and Figure 39 show the two typical arrangements, with vertical and horizontal axes. These arrangements are treated in more detail in the following subclauses.

14.2.3 Requirements on shape and surface conditions

14.2.3.1 General requirements

The standard sphere gap consists of two metal spheres of the same diameter D, their shanks, operating gear, insulating supports, supporting frame, and leads for connection to the point at which the voltage is to be measured. Standard values of D are 2 cm, 5 cm, 6.25 cm, 10 cm, 12.5 cm, 15 cm, 25 cm, 50 cm, 75 cm, 100 cm, 150 cm, and 200 cm. The spacing between the spheres is designated S.

The spheres shall be made so that their surfaces are smooth (as described below) and their curvature is uniform.

The tolerances on size and shape usually need to be checked only when the spheres are new or following repair. Any suitable instrument (e.g., spherometer) may be used. The diameter of each sphere shall not differ by more than 2% from the nominal value. A medium grade mechanical surface finishing (roughness R_{max} below 10 μm) is considered to be adequate. The spheres shall be reasonably free from surface irregularities with particular attention given to the region of the sparking point.

NOTE—Any minor damage outside the sparking point region does not alter the sphere-gap performance.

14.2.3.2 Condition of the sphere surfaces in the sparking point region

The sparking point region is defined by a circle such as would be drawn on the spheres by a pair of dividers set to an opening of 0.3 D and centered on the sparking point. The surfaces of the spheres in the sparking point region shall be cleaned and dried but need not be polished. The surface shall be rubbed with fine abrasive paper and the resulting dust removed with lint-free cloth; any trace of oil or grease shall be removed with a solvent.

In normal use, the surfaces of the spheres become roughened and pitted. If the spheres become excessively roughened or pitted in use, they shall be repaired or replaced. When the sphere gap is used, it will normally be sufficient to examine the surface by touch and visual inspection.

Moisture may condense on the surface of the sparking points in conditions of high relative humidity causing measurements to become erratic.

14.2.4 General arrangement of a vertical sphere gap for measurement

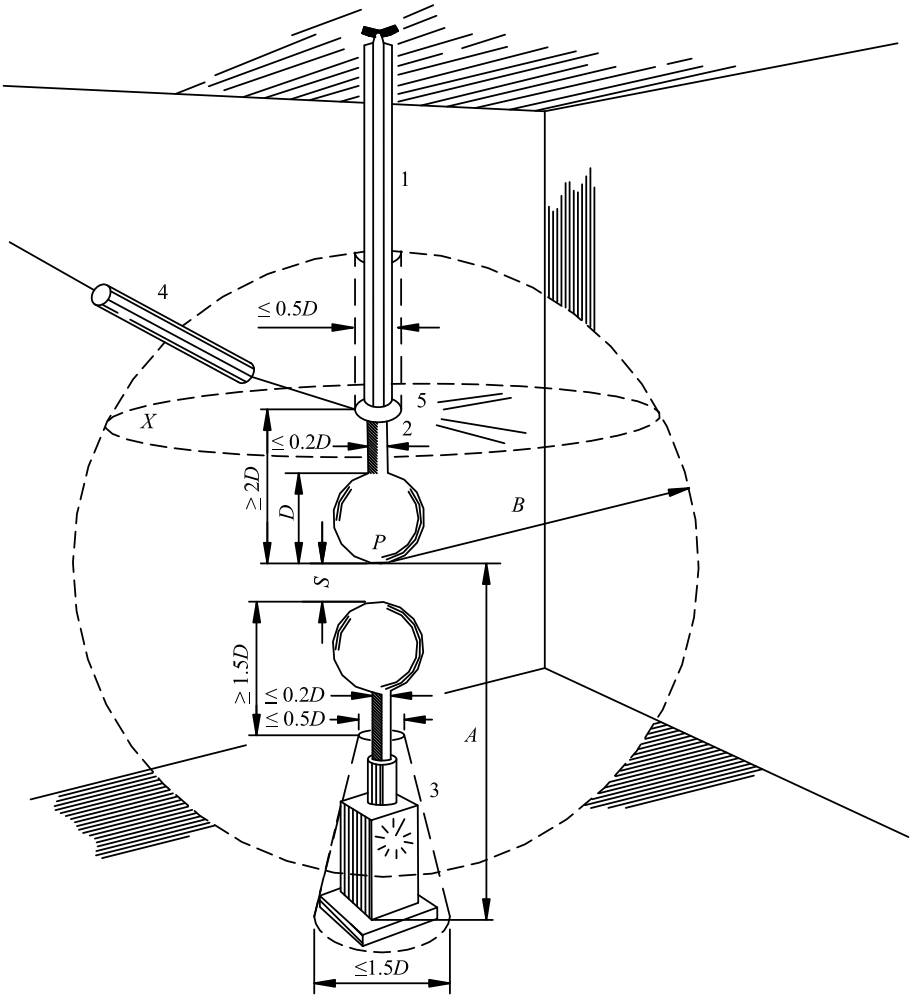
When the spheres are arranged vertically, the shank of the high-voltage sphere shall be free from sharp edges or corners and the diameter of the shank shall not exceed 0.2 D over a length D. This requirement is made in order to reduce the influence of the high-voltage shank on the disruptive discharge voltage. If a stress distributor (corona shield) is used at the end of the shank, its greatest dimension, perpendicular to the axis of the spheres, shall not exceed 0.5 D and shall be at least 2 D from the sparking point of the high-voltage sphere.

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The grounded shank and operating gear have a smaller effect than those on the high-voltage sphere, and their dimensions are therefore less important. Figure 38 gives the limits of size of the components of a typical vertical sphere gap.

The sphere shanks shall be visually in line.



1) Insulating support
2) Sphere shank
3) Operating gear, showing maximum dimensions
4) High-voltage connection with series resistor

P Sparking point of high-voltage sphere
A Height of *P* above ground plane
B Radius of space free from external structures
X Item 4) not to pass through this plane within a distance *B* from *P*

NOTE—The figure is drawn to scale for 100 cm sphere gap at radius spacing.

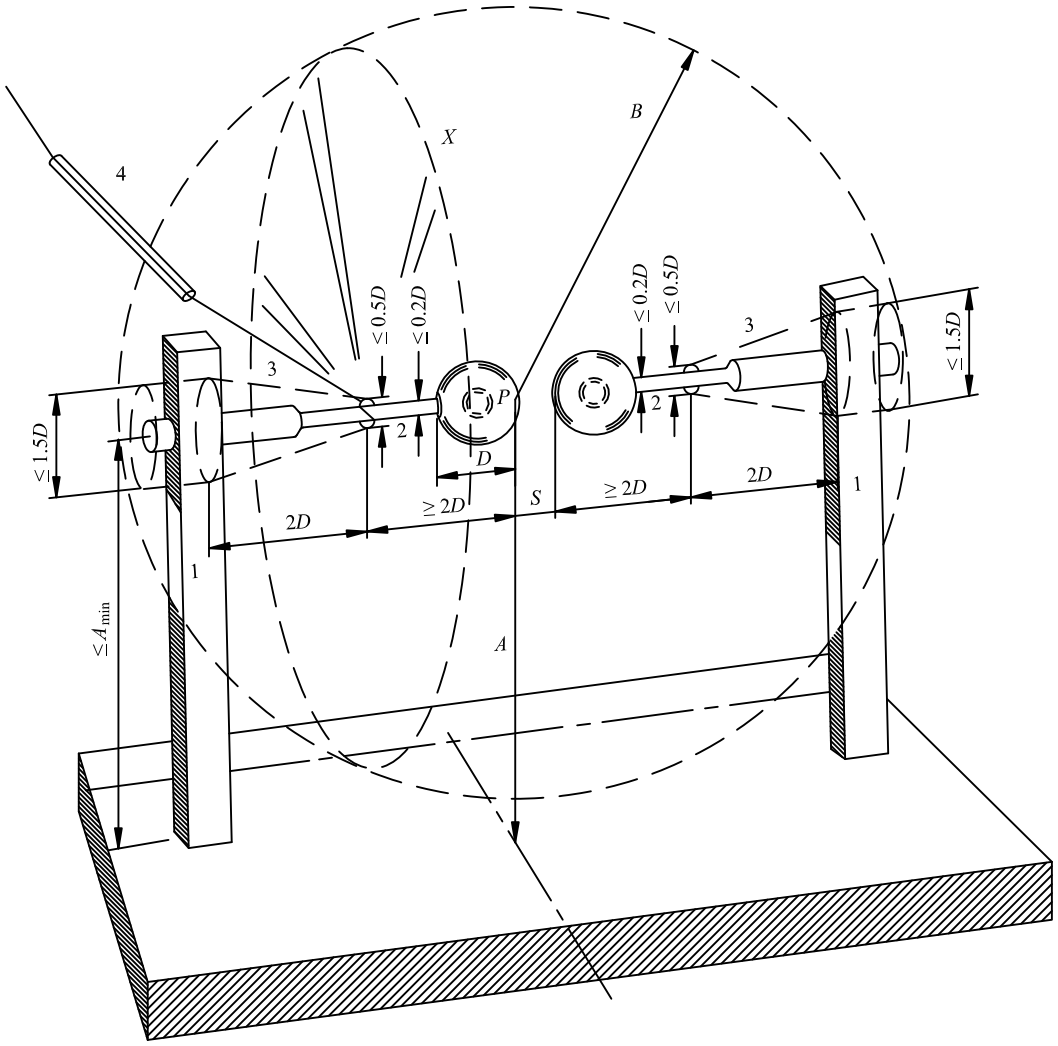
Figure 38 —Vertical sphere gap

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14.2.5 General arrangement of a horizontal sphere gap for measurement

When the spheres are arranged horizontally, the limiting dimensions of a typical sphere gap are given in Figure 39. They are the same for both sides of the gap. The sphere shanks shall be visually in line.



1) Insulating support
2) Sphere shank
3) Operating gear, showing maximum dimensions
4) High-voltage connection with series resistor

P Sparking point of high-voltage sphere
A Height of *P* above ground plane
B Radius of space free from external structures
X Item 4) not to pass through this plane within a distance *B* from *P*

NOTE—The figure is drawn to scale for a 25 cm sphere gap at radius spacing.

Figure 39 —Horizontal sphere gap

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14.2.6 Height of the spheres above the horizontal earth plane

The height *A* of the sparking point of the high-voltage sphere above the earth plane of the laboratory floor shall be within the limits given in Table 11.

Table 11—Clearance limits

Sphere diameter *D* (cm)	Minimum value of height *A*	Maximum value of height *A*	Minimum value of distance *B*
Up to 6.25	7 *D*	9 *D*	14 *S*
10 to 15	6 *D*	8 *D*	12 *S*
25	5 *D*	7 *D*	10 *S*
50	4 *D*	6 *D*	8 *S*
75	4 *D*	6 *D*	8 *S*
100	3.5 *D*	5 *D*	7 *S*
150	3 *D*	4 *D*	6 *S*
200	3 *D*	4 *D*	6 *S*

If the sphere-gap is mounted with the earthed sphere nearest to the ceiling, and if other surfaces such as walls and the floor are at a considerably greater distance, then the ceiling shall be regarded as the horizontal plane, from which the distance *A* is measured downwards.

NOTE 1—At small sphere-gap spacings, grounded objects of small size in the neighborhood of the gap affect the results insignificantly, but at greater spacings the presence of large areas such as walls, even at the distance *B*, have an important effect. The sphere gap shall, therefore, be erected in an open laboratory with not more than one wall at the distance *B*, and with the other walls at greater distances. The calibrations given in Table 12 and Table 13 have been based on experiments made under these conditions and they will be seriously in error if the sphere gap is placed, for instance, in a cylindrical container of radius *B*, except when the spacing is very small.

NOTE 2—For the measurement of very high voltages, it may be necessary to increase *A* and *B* above the minimum values given in Table 11, as these are not always sufficient to prevent disruptive discharge to grounded objects, especially those with sharp edges or corners.

14.2.7 Clearance around the spheres

The distance from the sparking point of the high-voltage sphere to any extraneous objects (such as ceiling, walls, and any energized or grounded equipment), and also to the supporting frame work for the spheres, if this is made of conducting material, shall not be less than the value of distance *B* in Table 11. Except as permitted below, *B* should not be less than 2 *D*, regardless of the value of *S*.

Supporting frameworks made of insulating material are exempt from this requirement, provided that they are clean and dry and provided that the spheres are used for the measurement of alternating or impulse voltages only. The distance *B* between the sparking point of the high-voltage sphere and the framework may then be less than is prescribed in Table 11. However, it shall not be less than 1.6 *D*.

The peak values of disruptive discharge voltages in Table 12 and Table 13 are valid for clearances around the spheres within the limits given in Table 11.

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The test conditions, principally the laboratory size, may make it impossible for the values of *A* and *B* to comply with the minimum requirements in Table 11. Such sphere gaps can be used, provided that either the conventional deviation *z* meets the requirements of 14.3 and 14.4, or that the uncertainty in the values for disruptive discharge in Table 12 and Table 13 are suitably increased.

The circuit should be arranged so that at the test voltage there is:

— No disruptive discharge to other objects.

— No visible leader discharge from the high-voltage lead or the shank within the space defined by *B*.

— No visible discharge from other earthed objects extending into the space defined by *B*.

14.2.8 Grounding

One sphere normally shall be connected directly to ground. Low ohmic shunts may be connected between the sphere and ground for the measurement of current.

14.2.9 High-voltage conductor

The high-voltage conductor, including any series resistor not in the shank itself, shall be connected to a point on the shank at least 2 *D* distant from the sparking point of the high-voltage sphere. Within the region where the distance to the sparking point of the high-voltage sphere is less than *B*, the high-voltage conductor (including the series resistor, if any) shall not pass through the plane normal to the axis of the sphere gap and situated at a distance 2 *D* from the sparking point of the high-voltage sphere. See Figure 38 and Figure 39 where the plane is shown.

14.3 Use of the sphere gap to measure the peak value of alternating voltage at power frequency

14.3.1 General procedure

The voltage shall be applied with an amplitude low enough to cause no disruptive discharge when the supply is energized, and it is then raised sufficiently slowly for the low-voltage indicator to be read accurately at the instant of disruptive discharge of the gap.

A minimum number of 10 successive disruptive discharge voltages shall be recorded in order that the mean value and conventional deviation *z* can be evaluated. The value of the conventional deviation *z* shall be less than 1% of the mean value.

The interval between voltage applications shall not be less than 30 seconds. The total time from the first to the last successive application used in a mean value calculation shall be kept to a minimum to avoid the influence of changing environmental conditions.

14.3.2 Protective resistor for measurement of alternating voltages

Precautions shall be taken to reduce the pitting of the spheres, and to prevent superimposed oscillations, which may cause erratic disruptive discharges. For these purposes, a resistance of 0.1 MΩ to 1.0 MΩ shall be connected in series with the sphere gap. This range of resistance values applies to measurements of

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alternating voltages at power frequencies, because the values of the resistance results in a negligible voltage drop.

The protective resistor shall be placed as near as possible to the shank of the sphere and connected directly to it. It shall not be placed in the common connection from the voltage source to the sphere gap and to the test object.

When streamer discharges are present in the test circuit, series resistance is particularly important in order to reduce the effect of the consequent transient over-voltage on the operation of the sphere-gap. When such discharges are not present in the test circuit or in the test specimen, the value of resistance may be reduced to a value that prevents excessive burning of the spheres by disruptive discharges.

14.4 Measurement of peak value of full lightning and switching impulse voltages using sphere gaps

14.4.1 General procedure

The 50% disruptive discharge voltage, $V_{50,}$ and the conventional deviation z shall be determined. The value of the conventional deviation z shall be not more than 1% of the mean value of the disruptive discharge voltage for full lightning impulse voltages and not more than 1.5% of the mean value of the disruptive discharge voltage for switching impulse voltages.

A multiple level test shall be used to reduce the conventional deviation value. A minimum of 10 voltage applications at each of five voltage levels in approximately 1% steps of the expected disruptive discharge value is needed to obtain V_{50} and to check the conventional deviation z.

The test can also be done by an up-and-down-test with a minimum of 20 voltage applications at approximately 1% steps of the expected V_{50} voltage. The criterion for the conventional deviation z shall be checked by applying 15 impulses at a voltage level of V_{50} - 1% for lightning impulse voltages and V_{50} - 1.5% for switching impulse voltages. There shall be not more than two disruptive discharges.

The interval between voltage applications shall be not less than 30 seconds. The total time from the first to the last successive application used in a mean value calculation shall be kept to a minimum to avoid the influence of changing environmental conditions.

NOTE—If, in a particular test, the sphere gap is used at several space settings, the criterion for the conventional deviation z should be checked for the smallest and largest gap distances.

14.4.2 Protective series resistor for measurement of impulse voltages

Series resistance is needed with large diameter spheres to eliminate voltage oscillations in the sphere gap circuit. Such oscillations may cause a higher voltage to occur between the spheres and, if connected, across the test object. This phenomenon is usually of minor importance for smaller spheres, unless they are used with long connecting leads. Series resistance may also be needed to reduce the steepness of the voltage collapse, as it might introduce undesirable stresses in the test object.

The resistor shall have a non-inductive construction (not more than 30 μH) and its resistance should not exceed 500 Ω. For the position of the resistor in the circuit, see 14.2.9.

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14.5 Reference voltage values in Table 12 and Table 13 for sphere gaps

14.5.1 General information

The disruptive discharge voltages for various spacing between spheres are given in Table 12 and Table 13 for the standard atmospheric temperature and pressure conditions:

— Temperature t_0 = 20 °C

— Pressure b_0 = 101.3 kPa

The values in Table 12 and Table 13 were obtained under conditions of absolute humidity between 5 g/m^3 and 12 g/m^3 with an average of 8.5 g/m^3.

Table 12 gives the peak value of disruptive discharge voltages (V_{50} values in impulse tests) in kV for:

— Alternating voltages at power frequencies.

— Full lightning and switching impulse voltages of negative polarity (as defined in this standard).

Table 13 gives the peak value of disruptive discharge voltages (V_{50} values) in kV for:

— Full lightning and switching impulse voltages of positive polarity as defined in this standard.

Table 12 and Table 13 are not valid for the measurement of impulse voltages below 10 kV.

14.5.2 Accuracy of values in Table 12 and Table 13

The values in Table 12 and Table 13 have been accepted as an international consensus reference standard of measurement.

The values for disruptive discharge voltage given in Table 12 and Table 13 have an estimated uncertainty of 3% for a level of confidence not less than 95% for alternating and impulse voltages.

Some values are given in Table 12 and Table 13 for spacings between 0.5 D and 0.75 D. No level of confidence is assigned to the values in brackets.

As it may be difficult to measure and adjust the gap with sufficient accuracy if the ratio of spacing to diameter is very small, it is recommended that the spacing should not be less than 0.05 D.

14.5.3 Air density correction factor

Disruptive discharge voltages corresponding to a given spacing under atmospheric conditions other than those specified above are obtained by multiplying the values in Table 12 and Table 13 by a correction factor corresponding to the relative air density δ.

The relative air density δ is defined by:

$$\delta = \frac{b}{b_0} \times \frac{273 + t_0}{273 + t} \tag{66}$$

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where

b and t represent the actual atmospheric pressure and temperature during the test

the atmospheric pressures b and b_0 are expressed in the same units (kilopascals)

t and t_0 are the temperatures in degrees Celsius

14.5.4 Humidity correction factor

The disruptive discharge voltage of a sphere gap increases with absolute humidity at a rate of 0.2% per g/m^3. The average value of absolute humidity h under which the values in Table 12 and Table 13 were obtained is 8.5 g/m^3. The values in Table 12 and Table 13 shall be corrected for humidity by multiplying the values in those tables by the humidity correction factor k given by the following equation:

$$k = 1 + \left[0.002\left(\frac{h}{\delta} - 8.5 \right) \right] \tag{67}$$

with the ambient absolute humidity h in g/m^3.

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Table 12— Peak values of disruptive discharge voltages (V_{50} values in impulse tests) in kV for alternating voltages at power frequencies, full lightning, and switching impulse voltages of negative polarity

Sphere gap spacing cm	Sphere diameter cm											
	2	5	6.25	10	12.5	15	25	50	75	100	150	200
0.05	2.8											
0.10	4.7											
0.15	6.4											
0.20	8.0	8.0										
0.26	9.6	9.6										
0.30	11.2	11.2										
0.40	14.4	14.3	14.2									
0.50	17.4	17.4	17.2	16.8	16.8	16.8						
0.60	20.4	20.4	20.2	19.9	19.9	19.9						
0.70	23.2	23.4	23.2	23.0	23.0	23.0						
0.80	25.8	26.3	26.2	26.0	26.0	26.0						
0.90	28.3	29.2	29.1	28.9	28.9	28.9						
1.0	30.7	32.0	31.9	31.7	31.7	31.7	31.7					
1.2	(35.1)	37.6	37.5	37.4	37.4	37.4	37.4					
1.4	(38.5)	42.9	42.9	42.9	42.9	42.9	42.9					
1.5	(40.0)	45.5	45.5	45.5	45.5	45.5	45.5					
1.6		48.1	48.1	48.1	48.1	48.1	48.1					
1.8		53.0	53.5	53.5	53.5	53.5	53.5					
2.0		57.5	58.5	59.0	59.0	59.0	59.0	59.0	59.0			
2.2		61.5	63.0	64.5	64.5	64.5	64.5	64.5	64.5			

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Table 12—Peak values of disruptive discharge voltages (V_{50} values in impulse tests) in kV for alternating voltages at power frequencies, full lightning, and switching impulse voltages of negative polarity *(continued)*

Sphere gap spacing cm	Sphere diameter cm											
	2	5	6.25	10	12.5	15	25	50	75	100	150	200
2.4		65.5	67.5	69.5	70.0	70.0	70.0	70.0	70.0			
2.6		(69.0)	72.0	74.5	75.0	75.5	75.5	75.5	75.5			
2.8		(72.5)	76.0	79.5	80.0	80.5	81.0	81.0	81.0			
3.0		(75.5)	79.5	84.0	85.0	85.5	86.0	86.0	86.0	86.0		
3.5		(82.5)	(87.5)	95.0	97.0	98.0	99.0	99.0	99.0	99.0		
4.0		(88.5)	(95.0)	105	108	110	112	112	112	112		
4.5			(101)	115	119	122	125	125	125	125		
5.0			(107)	123	129	133	137	138	138	138	138	
5.5				(131)	138	143	149	151	151	151	151	
6.0				(138)	146	152	161	164	164	164	164	
6.5				(144)	(154)	161	173	177	177	177	177	
7.0				(150)	(161)	169	184	189	190	190	190	
7.5				(155)	(168)	177	195	202	203	203	203	
8.0					(174)	(185)	206	214	215	215	215	
9.0					(185)	(198)	226	239	240	241	241	
10					(195)	(209)	244	263	265	266	266	266
11						(219)	261	286	290	292	292	292
12						(229)	275	309	315	318	318	318
13							(289)	331	339	342	342	342
14							(302)	353	363	366	366	366
15							(314)	373	387	390	390	390
16							(326)	392	410	414	414	414
17							(337)	411	432	438	438	438
18							(347)	429	453	462	462	462
19							(357)	445	473	486	486	486
20							(366)	460	492	510	510	510
22								489	530	555	560	560
24								515	565	595	610	610
26								(540)	600	635	655	660
28								(565)	635	675	700	705

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Table 12—Peak values of disruptive discharge voltages (V_{50} values in impulse tests) in kV for alternating voltages at power frequencies, full lightning, and switching impulse voltages of negative polarity *(continued)*

Sphere gap spacing cm	Sphere diameter cm											
	2	5	6.25	10	12.5	15	25	50	75	100	150	200
30								(585)	665	710	745	750
32								(605)	695	745	790	795
34								(625)	725	780	835	840
36								(640)	750	815	875	885
38								(655)	(775)	845	915	930
40								(670)	(800)	875	955	975
45									(850)	945	1050	1080
50									(895)	1010	1130	1180
55									(935)	(1060)	1210	1260
60									(970)	(1110)	1280	1340
65										(1160)	1340	1410
70										(1200)	1390	1480
75										(1230)	1440	1540
80											(1490)	1600
85											(1540)	1660
90											(1580)	1720
100											(1660)	1840
110											(1730)	(1940)
120											(1800)	(2020)
130												(2100)
140												(2180)
150												(2250)

NOTE 1—Values are not valid for impulse voltages below 10 kV.

NOTE 2—Figures in brackets, which are for spacings of more than 0.5 D, are of larger uncertainty.

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Table 13—Peak values of disruptive discharge voltages (V_{50} values in impulse tests) in kV for full lightning and switching impulse voltages of positive polarity

Sphere gap spacing cm	Sphere diameter cm											
	2	5	6.25	10	12.5	15	25	50	75	100	150	200
0.05												
0.10												
0.15												
0.20												
0.25												
0.30	11.2	11.2										
0.40	14.4	14.3	14.2									
0.50	17.4	17.4	17.2	16.8	16.8	16.8						
0.60	20.4	20.4	20.2	19.9	19.9	19.9						
0.70	23.2	23.4	23.2	23.0	23.0	23.0						
0.80	25.8	26.3	26.2	26.0	26.0	26.0						
0.90	28.3	29.2	29.1	28.9	28.9	28.9						
1.0	30.7	32.0	31.9	31.7	31.7	31.7	31.7					
1.2	(35.1)	37.8	37.6	37.4	37.4	37.4	37.4					
1.4	(38.5)	43.3	43.2	42.9	42.9	42.9	42.9					
1.5	(40.0)	46.2	45.9	45.5	45.5	45.5	45.5					
1.6		49.0	48.6	48.1	48.1	48.1	48.1					
1.8		54.5	54.0	53.5	53.5	53.5	53.5					
2.0		59.5	59.0	59.0	59.0	59.0	59.0	59.0	59.0			
2.2		64.0	64.0	64.5	64.5	64.5	64.5	64.5	64.5			
2.4		69.0	69.0	70.0	70.0	70.0	70.0	70.0	70.0			
2.6		(73.0)	73.5	75.5	75.5	75.5	75.5	75.5	75.5			
2.8		(77.0)	78.0	80.5	80.5	80.5	81.0	81.0	81.0			
3.0		(81.0)	82.0	85.5	85.5	85.5	86.0	86.0	86.0	86.0		
3.5		(90.0)	(91.5)	97.5	98.0	98.5	99.0	99.0	99.0	99.0		
4.0		(97.5)	(101)	109	110	111	112	112	112	112		
4.5			(108)	120	122	124	125	125	125	125		
5.0			(115)	130	134	136	138	138	138	138	138	
5.5				(139)	145	147	151	151	151	151	151	
6.0				(148)	155	158	163	164	164	164	164	

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Table 13—Peak values of disruptive discharge voltages (V_{50} values in impulse tests) in kV for full lightning and switching impulse voltages of positive polarity *(continued)*

Sphere gap spacing cm	Sphere diameter cm											
	2	5	6.25	10	12.5	15	25	50	75	100	150	200
6.5				(156)	(164)	168	175	177	177	177	177	
7.0				(163)	(173)	178	187	189	190	190	190	
7.5				(170)	(181)	187	199	202	203	203	203	
8.0					(189)	(196)	211	214	215	215	215	
9.0					(203)	(212)	233	239	240	241	241	
10					(215)	(226)	254	263	265	266	266	266
11						(238)	273	287	290	292	292	292
12						(249)	291	311	315	318	318	318
13							(308)	334	339	342	342	342
14							(323)	357	363	366	366	366
15							(337)	380	387	390	390	390
16							(350)	402	411	414	414	414
17							(362)	422	435	438	438	438
18							(374)	442	458	462	462	462
19							(385)	461	482	486	486	486
20							(395)	480	505	510	510	510
22								510	545	555	560	560
24								540	585	600	610	610
26								570	620	645	655	660
28								(595)	660	685	700	705
30								(620)	695	725	745	750
32								(640)	725	760	790	795
34								(660)	755	795	835	840
36								(680)	785	830	880	885
38								(700)	(810)	865	925	935
40								(715)	(835)	900	965	980
45									(890)	980	1060	1090
50									(940)	1040	1150	1190
55									(985)	(1100)	1240	1290
60									(1020)	(1150)	1310	1380

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Table 13—Peak values of disruptive discharge voltages (V_{50} values in impulse tests) in kV for full lightning and switching impulse voltages of positive polarity *(continued)*

Sphere gap spacing cm	Sphere diameter cm											
	2	5	6.25	10	12.5	15	25	50	75	100	150	200
65										(1200)	1380	1470
70										(1240)	1430	1550
75										(1280)	1480	1620
80											(1530)	1690
85											(1580)	1760
90											(1630)	1820
100											(1720)	1930
110											(1790)	(2030)
120											(1860)	(2120)
130												(2200)
140												(2280)
150												(2350)

NOTE—The figures in brackets, which are for spacings of more than 0.5 *D* are of larger uncertainty.

14.6 Standard rod-rod gap for measurement of direct voltage

14.6.1 General arrangement of a rod-rod gap

The general arrangement of a rod-rod gap shall be as shown in either Figure 40 (vertical gap) or Figure 41 (horizontal gap).

The rods shall be made of steel or brass, with a solid square section, sides between 10 mm and 25 mm, and have a common axis. The ends shall be cut at right angles to the axis leaving the edges sharp in order to get a reproducible breakdown mechanism.

The clearance from the tip of the high-voltage electrode to grounded objects and walls, other than the ground plane, shall be not less than 5 meters.

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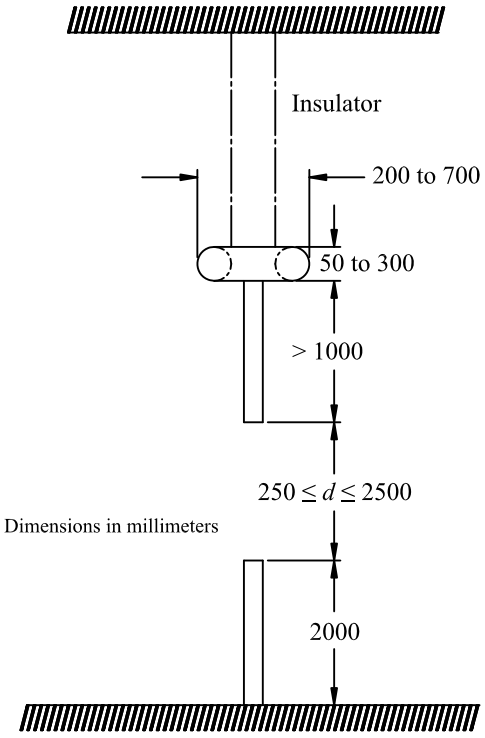


Figure 40 —Vertical arrangement of the rod-rod gap

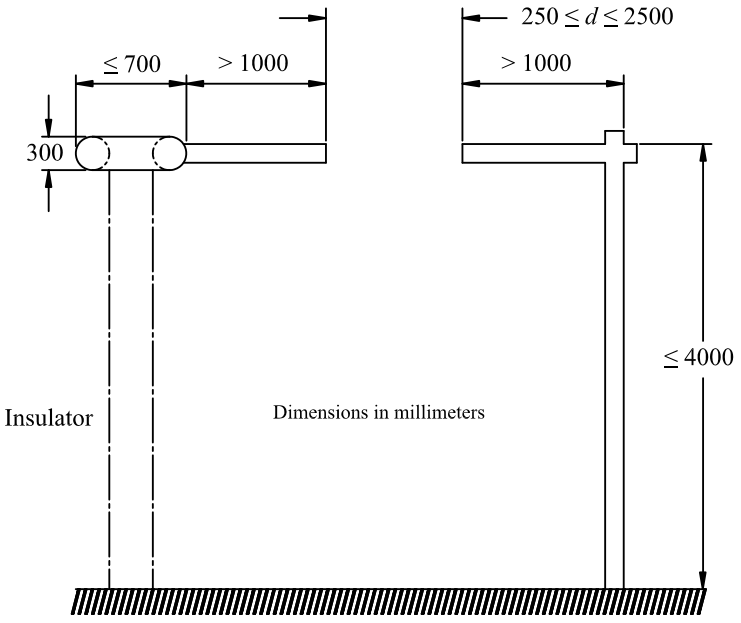


Figure 41 —Horizontal arrangement of the rod-rod gap

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14.6.2 Reference values

The disruptive discharge voltage V_0 for positive and negative direct voltage and for either the vertical or the horizontal gap, at standard reference atmosphere, is given by:

$$V_0 = 2 + 0.534d \tag{68}$$

where

V_0 is in kilovolts

d is the gap spacing in millimeters

Equation (68) is valid for gap distances d between 250 mm and 2500 mm and for a humidity range h/δ between 1 g/m^3 and 13 g/m^3. Under these conditions, the disruptive discharge voltage V_0 has an estimated uncertainty of ± 3% for a level of confidence not less than 95%.

The rod-rod gap shall not be used as an approved measuring device at gap spacing less than 250 mm because of the absence of streamer pre-discharges. There is no experimental evidence to support its use at gap spacings greater than 2500 mm.

14.6.3 Measurement procedure

The spacing d between the rods shall be set and the voltage applied and raised so that the time interval between 75% and 100% of the discharge voltage is approximately 1 minute.

Ten readings of the voltage at the instant of sparkover shall be taken with the voltage indicating device of the measuring system. The voltage, at standard reference atmosphere, corresponding to the mean of these 10 values is given by Equation (68). This voltage shall be corrected for the actual atmospheric conditions by taking into account the air density δ (see 14.5.3) and the humidity correction factor k given by the following equation:

$$k = 1 + \left[0.014 \left(\frac{h}{\delta} - 11 \right) \right] \tag{69}$$

for a humidity range h/δ between 1 g/m^3 and 13 g/m^3.

Breakdown voltage values V measured under actual conditions with the temperature t, the pressure b and the absolute humidity h are reported to standard reference atmosphere as follows:

$$V_0 = \frac{V}{\delta \times k} \tag{70}$$

14.7 Use of standard air gaps for performance checks of approved measuring systems

When a standard air gap is used to make performance checks on a measuring system whose performance is known only insofar as it meets the requirements of an approved measuring system, the two elements of the

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check circuit will each have an assigned uncertainty of 3% and therefore differences exceeding this figure could arise in the comparison.

However, when performance checks on the same approved measuring system are repeated, the differences between subsequent measurements, after correction for all atmospheric conditions, can be expected to be appreciably less than 3%.

15. Statistical treatment of test results

15.1 Classification of tests

15.1.1 Class 1: Multiple-level tests

In a Class 1 test, m_i substantially equal voltage stresses are applied at each of n voltage levels V_i (i = 1, 2, …, n) of a difference $\Delta V = V_{i+1} - V_i$ (e.g., lightning impulses). While this procedure is usually employed with impulse voltages, some tests with alternating and direct voltages also fall into this class.

NOTE—The parameters should be selected as follows: $n \geq 5$, $m \geq 10$; $\Delta V = (0.01 \ldots 0.06)\ V_{50}$

The test results are the n numbers of voltage applications (m_i) and the corresponding numbers of disruptive discharges (d_i) at each voltage level V_i.

15.1.2 Class 2: Up-and-down tests

In a Class 2 test, n groups of m substantially equal voltage stresses are applied at voltage levels V_i (i = 1, 2, …, l). The voltage level for each succeeding group of stresses is increased or decreased by a small amount, ΔV, according to the result of the previous group of stresses.

Two testing procedures are commonly used. They are the withstand procedure, aimed at finding voltage levels corresponding to low disruptive-discharge probabilities, and the discharge procedure, which finds voltage levels corresponding to high disruptive-discharge probabilities. In the withstand procedure, the voltage level is increased by the amount ΔV if no disruptive discharge occurs in a group of m voltage applications; otherwise, the voltage level is decreased by the same amount. In the discharge procedures, the voltage level is increased by ΔV if one or more withstands occur; otherwise, it is decreased by the same amount.

Where m = 1, the two procedures become identical and correspond to the up-and-down 50% disruptive-discharge voltage test.

Tests with other values of m are also used to determine voltages corresponding to other disruptive-discharge probabilities. The results are the numbers of stress groups (k_i) applied at the voltage levels V_i. The first level of V_i taken into account is that at which at least two groups of stresses were applied. The total number of useful groups is:

$$n = \sum_{i=1}^{l} k_i \quad \text{at the voltage levels } i = 1, 2, \ldots, l \tag{71}$$

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NOTE—Tests with $m = 7$ give the 10% and 90% disruptive discharge voltages which are defined as the withstand and disruptive discharge voltages respectively (see 8.4). The other parameters should be selected as $\Delta V = (0.01 \ldots 0.03)\ V_{50}$ and $n > 15$.

15.1.3 Class 3: Progressive stress tests

In a Class 3 test, a procedure leading to a disruptive discharge on the test object is applied n times. The test voltage may be increased continuously until a disruptive discharge occurs, or the test voltage may be held constant at some level until a disruptive discharge at a time t_i is observed. The results are the n values of voltage V_i or time t_i at which the disruptive discharge occurred ($n \geq 10$).

Such tests are made with continuously or stepwise increased direct, alternating, or stepwise increased impulse voltages. Tests where disruptive discharges occur on the front of the impulse fall into this class.

15.2 Statistical behavior of disruptive discharge

When p, the probability of a disruptive discharge during a given test procedure, depends only on the test voltage, V, the behavior of the test object can be characterized by a function $p(V)$ determined by the processes of discharge development. In practice, this disruptive discharge probability function can be represented mathematically by a theoretical probability distribution function characterized by at least two parameters, V_{50} and z. V_{50} is the 50% discharge voltage for which $p(V) = 0.5$, and z is the conventional deviation; $z = (V_{50} - V_{16})$ where V_{16} is the voltage for which $p(V) = 0.16$.

NOTE 1—Examples of $p(V)$ can be derived from the Gaussian (or Normal), the Weibull, or the Gumbel probability distribution functions. Experience shows that for $0.15 < p < 0.85$, most theoretical distributions can be considered equivalent. Special Weibull or Gumbel distributions are acceptable approximations to a Gaussian distribution having given V_{50} and z for p lying between 0.02 and 0.98. Beyond these limits little information is available.

NOTE 2—Sometimes, p is a function of two or more parameters (e.g., V and dV/dt). In such cases, no simple function can be used to describe p. Details of such cases may be found in the technical literature.

The function $p(V)$ and the parameters V_{50} and z can be estimated from tests with sufficient numbers of voltage applications, provided that the characteristics of the test object remain constant throughout the tests.

In practice, the number of voltage applications is usually limited, and the estimates of V_{50} and z based on an assumed form of $p(V)$ will be subject to statistical uncertainties.

15.2.1 Confidence limits

If a parameter y is estimated from n test results, upper and lower confidence limits y_U and y_L can be defined, with the probability C that the true value of y is within these limits. C is termed the confidence level, and it is the probability that the true value of y lies within the limits y_U and y_L. The range $e_r = (y_U - y_L)$ delivers the width of the confidence band.

Usually, C is taken as 0.95 (or 0.90), and the corresponding limits are called the 95% (or 90%) confidence limits.

The width (e_r) of the confidence band depends on both n and the value of the conventional deviation (z). The conventional deviation should be estimated when possible from tests made under realistic conditions. In general, the larger the number of tests made, the better will be the estimate of z. It should, however, be remembered that during a protracted test series, ambient conditions may change to an extent that offsets the gain in accuracy from the increased number of tests.

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NOTE—Since accurate estimation of z from a limited series of tests is not possible, values estimated from the pooled results of many tests are often given by the relevant apparatus committees.

The half-width of the confidence band may be combined with estimates of other uncertainties (e.g., measuring uncertainty) to define the overall uncertainty for the determination of a particular parameter.

15.3 Analysis of test results

This subclause is applicable to cases in which the results of tests can be regarded as independent estimates [i.e., where the n^{th} result is not influenced by what may have occurred in the $(n-1^{th})$ or $(n-j^{th})$ tests].

15.3.1 Treatment of results from Class 1 tests

In this case, the discharge frequency $f_i = d_i/m_i$ at a voltage level V_i is taken as an estimate of $p(V)$, the discharge probability at the voltage level V_i. The n estimates of $p(V)$ obtained in a Class 1 test can then be fitted to an assumed probability distribution function $p(V)$, and the parameters V_{50} and z can be determined.

This may be done by plotting f_i versus V_i on a special graph paper designed to give a straight line plot when the probability estimates conform to a particular probability distribution function $p(V)$. A well-known example is Gaussian or Normal probability paper, which yields a straight line plot for estimates conforming to the Gaussian distribution function:

$$p(V) = \frac{1}{z\sqrt{2\pi}} \int_{-\infty}^{V} e^{-\frac{1}{2}\left(\frac{v-V_{50}}{z}\right)^2} dv \tag{72}$$

NOTE—Normal probability papers do not have ordinate scales embracing the values $p = 0$ or $p = 1$. Accordingly, tests at voltage levels causing all discharges ($d_i = m_i$) or no discharges ($d_i = 0$) cannot be plotted directly. A possible way of using these results is to combine them with values obtained for an adjacent voltage level and to plot them as the weighted mean voltage.

Alternatively, analytical fitting techniques involving the least-squares method or likelihood methods (see 15.4) may be used to find V_{50}, z, and the confidence limits of these estimates.

In any case, adequate methods (such as conventional regression coefficients or confidence limits) should be used to check if the assumed probability function fits the measured points with sufficient accuracy. Reference is made to the relevant technical literature.

As a general guide, the width of the confidence band tends to vary inversely as the square root of the number of voltage applications at each level (m_i) and inversely as the number of levels used (n). Note also that if all values of f_i differ from zero and unity, with ten voltage applications ($m = 10$) at each of five levels ($n = 5$), the 95% confidence limits for V_{50} would be:

$$(V_{50}^{*} - 0.75z^{*}) \le V_{50} \le (V_{50}^{*} + 0.75z^{*}) \tag{73}$$

and for z:

$$0.4z^{*} \le z \le 2.0z^{*} \tag{74}$$

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where

V^*_{50} is the estimate of V_{50} obtained by fitting the test results to an assumed discharge probability distribution function $p(V)$

z^* is the estimate of z obtained by fitting the test results to an assumed discharge probability distribution function $p(V)$

In addition, the width of the confidence band tends towards lower values for estimates of V_p in the vicinity of $p = 0.5$ or 50%.

15.3.2 Treatment of results from Class 2 tests

A Class 2 test provides an estimate of V_p, the voltage at which the disruptive discharge probability is p. V^*_p, the estimate of V_p, is given by:

$$V_p^* = \frac{\sum(k_i V_i)}{n} \tag{75}$$

where

k_i is the number of groups of stresses applied at the voltage level V_p

To avoid appreciable errors, the lowest voltage level taken into account should not differ from V^*_p by more than $2 \times \Delta V$.

The procedure for determining the withstand voltage, described in 15.1.2, provides an estimate of V_p for a disruptive discharge probability p given by:

$$p = 1 - \sqrt[m]{0.5} \tag{76}$$

while the procedure for determining the disruptive discharge voltage gives V_p for:

$$p = \sqrt[m]{0.5} \tag{77}$$

The values of p for which V_p can be estimated in up-and-down tests are limited by the requirement that m be an integer. Examples are given below in Table 14.

Table 14—Discharge probabilities in up-and-down testing

m =	70	34	14	7	4	3	2	1	
p =	0.01	0.02	0.05	0.10	0.15	0.20	0.30	0.50	(withstand procedure)
p =	0.99	0.98	0.95	0.90	0.85	0.80	0.70	0.50	(discharge procedure)

Procedures for estimating z and its confidence limits are also available but are not recommended for general use.

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15.3.3 Treatment of results from Class 3 tests

The result of a Class 3 test is usually a series of n voltages V_p from which the parameters V_{50} and z of a disruptive discharge probability function are to be determined. For a Gaussian (or Normal) distribution, estimates of the parameters V_{50} and z are given by:

$$V_{50}^{*} = \frac{\sum V_i}{n} \tag{78}$$

$$z^{*} = \sqrt{\sum \frac{(V_i - V_{50})^2}{n-1}} \tag{79}$$

For other distributions, likelihood methods can be employed to estimate V_{50} and z (see 15.4). The same expressions and methods apply in cases in which times to the occurrence of a disruptive discharge (t_i) are to be analyzed.

The confidence limits for Gaussian distributions (V^{*}_{50}, z^{*}) may be found using the Student's t or Chi-squared distributions as described in the technical literature.

As an example, in the case of a Gaussian distribution, the 95% confidence limits for the estimates of V_{50} and z obtained from a test with $n = 20$ are:

$$(V_{50}^{*} - 0.47z^{*}) \le V_{50} \le (V_{50}^{*} + 0.47z^{*}) \tag{80}$$

and for z:

$$0.76z^{*} \le z \le 1.46z^{*} \tag{81}$$

15.4 Application of likelihood methods

Likelihood methods may be used for the analysis of the results of all of the above classes of tests. These methods permit estimation of V_{50} and z, and hence V_p, once a discharge probability distribution function $p(V_i; V_{50}, z)$ is selected.

Furthermore, it is possible to use all the results obtained, and the confidence limits corresponding to any desired confidence level C can be found.

15.4.1 The likelihood function

For Class 1 and Class 2 tests, the number of disruptive discharges, d_i, and the number of withstands, w_i, found at each voltage level V_i are known. If the form of the disruptive discharge probability distribution function $p(V_i; V_{50}, z)$ is assumed, the probability of a discharge at the level V_i is $p(V_i; V_{50}, z)$ and the probability of a withstand is $1 - p(V_i; V_{50}, z)$. The likelihood function L_i corresponding to d_i discharges and w_i withstands occurring at a voltage level V_i is then:

$$L_i = p(V_i; V_{50}, z)^{d_i} \left[1 - p(V_i; V_{50}, z)\right]^{w_i} \tag{82}$$

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Since V_i, d_i, and w_i are known, L_i is a function of V_{50} and z only.

The likelihood of a complete set of results embracing n values of V_i then becomes:

$$L = L_1 L_2 ... L_i ... L_n = L(V_{50}, z) \tag{83}$$

For Class 3 tests, each voltage level V_i that appears in the results corresponds to a disruptive discharge. In general, a voltage level V_i will appear m_i times where $m_i > 1$. The likelihood (L) then becomes:

$$L = f(V_1; V_{50}, z)^{m_1} f(V_2; V_{50}, z)^{m_2} ... f(V_m; V_{50}, z)^{m_m} \tag{84}$$

where

$$f = \frac{dp}{dV} \tag{85}$$

Methods for calculating L from extensive sets of results by considering groups of results lying in a number of voltage intervals can be found in the technical literature.

15.4.2 Estimation of V_{50} and z

The best estimates of V_{50} and z are the values V^*_{50} and z^*, which maximize L.

These are frequently found by using a computer to make repeated calculations of L for assumed values of V^*_{50} and z^*. With V^*_{50} and z^* fixed, V_p corresponding to any desired value of disruptive discharge probability p can be found from the assumed discharge probability distribution function with $V_{50} = V^*_{50}$ and $z = z^*$. Methods for determining the confidence limits of V^*_{50} and z^* may be found in the technical literature. For the case of $C = 0.9$, the relationship $L(V_{50}; z) = 0.1L_{max}$ permits determination of these confidence limits.

NOTE—In addition to the analysis based on the Gaussian distribution (see 15.3.1) the maximum likelihood method also delivers reliable results for other theoretical probability functions (e.g., for the Weibull or the Gumbel distribution). For details see the relevant literature and available software.

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Annex A

(normative)

Procedure for calculating of parameters of lightning impulse voltages with superimposed oscillation on the peak

This annex describes procedures for calculation of the parameters of lightning impulse voltages with superimposed oscillations on the peak. The procedures are based on an empirically derived function that provides a means of calculating the effective stress imposed on insulation by varying degrees of overshoot or peak oscillations [B42] [B78]. This function is continuous, not single valued as was the single frequency 500 kHz function used in earlier revisions of this standard. The parameters determined using these procedures will therefore differ from those that would be obtained using those earlier methods.

A.1 Basis of the procedures

A smooth base curve $V_m(t)$ is first constructed through the applied voltage or recorded curve $V(t)$ and then subtracted from the applied voltage curve so as to yield its oscillatory components. The oscillatory components [i.e., the residual curve $R(t)$], is then filtered by a frequency dependent filter function to become $R_f(t)$, before being added back to the base curve to produce the test voltage curve $V_t(t)$, the curve or record from which the impulse parameters are derived.

The procedure is based on the empirical Equation (A.1) and Equation (A.2):

$$V_t = V_{mp} + k(f)(V_e - V_{mp}) \tag{A.1}$$

where

V_t is the test voltage, which is the peak value of the processed test voltage curve

V_{mp} is the peak value of the overshoot-free base curve

V_e is the extreme or maximum value of the record of the applied impulse voltage (i.e., the recorded curve)

$k(f)$ is the frequency dependent test voltage factor

The equation describes an effective test voltage value V_t that the insulation would be subjected to and with which the impulse parameters are derived.

The frequency dependent function of the test voltage factor is given by:

$$k(f) = \frac{1}{1 + af^2} \tag{A.2}$$

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where

f is the frequency in MHz

a is a coefficient with a value of 2.2

The graphic expression of the $k(f)$ function is shown in Figure A.1.

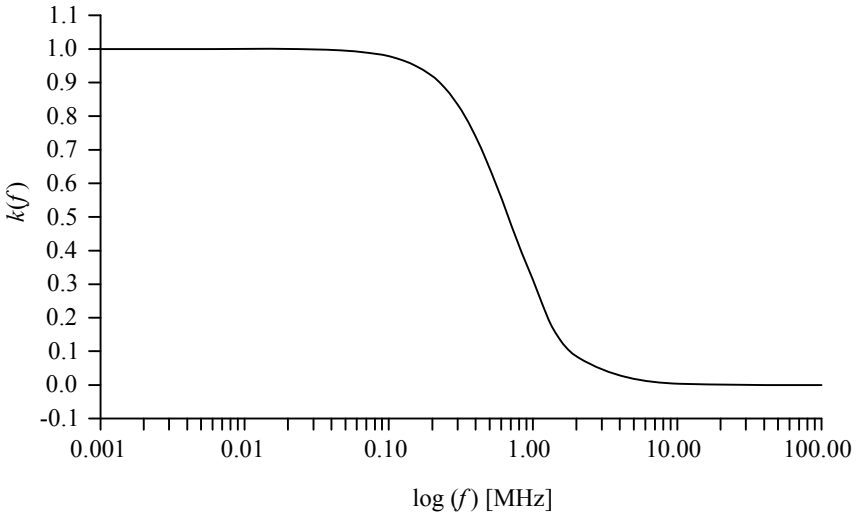


Figure A.1—Frequency dependency of the test voltage function *k*(*f*)

The test voltage equation, Equation (A.1) is applicable to impulses both with and without overshoot. For impulses without overshoot, the applied voltage is a smooth curve and has the form of a base curve without any residual oscillations to process. Such curves are unaffected by the residual filter function and yield impulse parameters that are unaffected by that function. The procedures are therefore transparent to smooth curves and so it is not necessary to pre-sort impulse prior to parameter derivation.

A.2 Procedure for calculation from digital waveforms

A.2.1 Description

This procedure is an implementation of Equation (A.1), and it is suggested for use for computer-aided calculation of impulses in digital form [B150].

$$V_t = Max\{V_m(t) + R_f(t)\} \quad \text{(A.3)}$$

where

V_t is as defined above

$V_m(t)$ is the record of the base curve obtained by an exponential curve fitting procedure

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$R_f(t)$ is the record of the filtered residual curve

The residual curve is obtained by subtracting $V_m(t)$ from the recorded curve [i.e., the applied voltage $V(t)$]. The transfer function of the filter applied to the residual curve is equal to that defined by Equation (A.2).

Then, the value of the test voltage V_t, and the values of the front time and the time to half-value, are determined as defined in Clause 8 from the processed waveform $V_t(t)$, termed the test voltage curve, given by $V_t(t) = V_m(t) + R_f(t)$.

The relative overshoot amplitude expressed as a percentage, β'(%), is determined from the relative difference between the peak value of the recorded curve V_e and the peak value of the base curve V_{mp} [i.e., $100(V_e - V_{mp}) / V_e$].

Graphical illustrations of the various waveforms are shown in Figure A.2, Figure A.3, and Figure A.4.

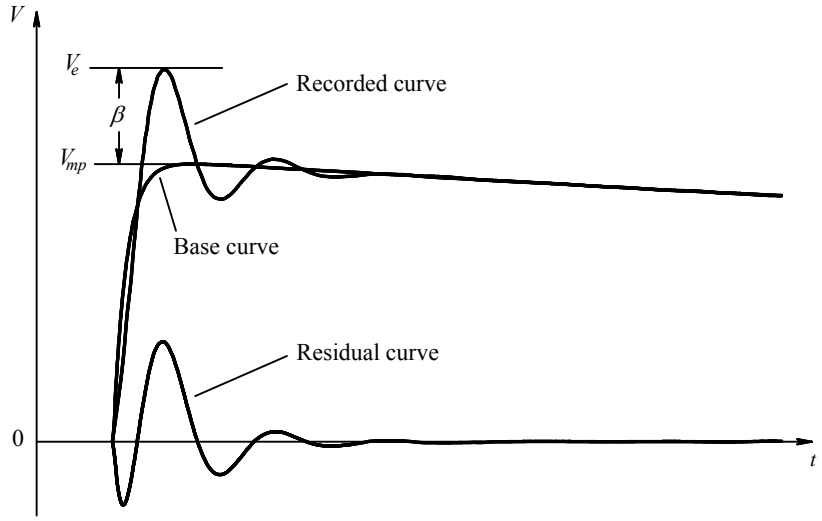


Figure A.2—Recorded and base curve showing overshoot and residual curve

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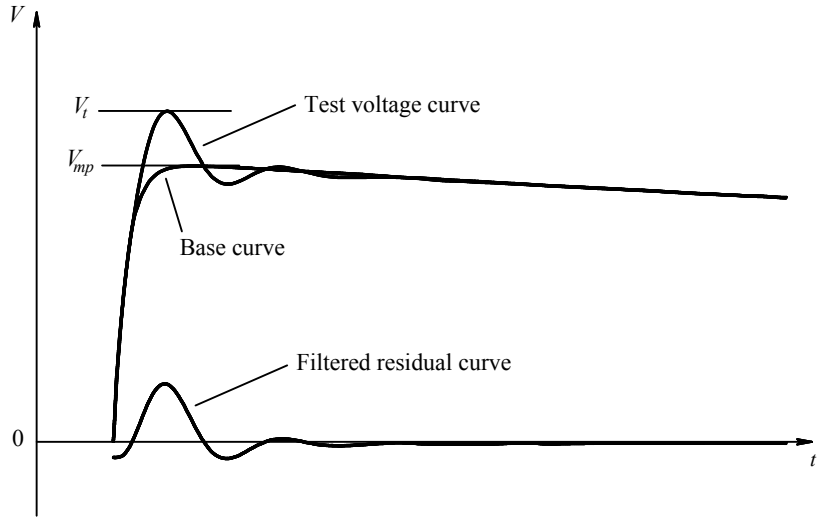


Figure A.3—Test voltage curve (addition of base curve and filtered residual curve)

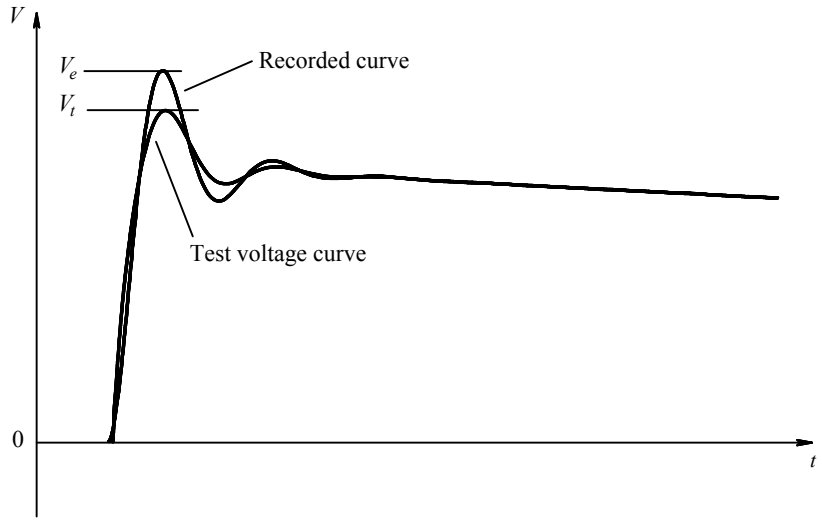


Figure A.4—Recorded and test voltage curves

A.2.2 Recommended steps for calculating full lightning impulse parameters

The following steps are recommended for calculating the impulse parameters from digitally recorded impulses using this procedure:

a) Find the extreme value V_e of the recorded curve $V(t)$.

b) Find the base level of the recorded curve by calculating the mean of the voltage values from the flat part or foot of the waveform at the beginning of the record.

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c) Find the last sample on the front having a voltage value less than 0.2 times the extreme value V_e, and discard data up to and including that sample. This is to remove the influence of any disturbance and slow voltage rise at the beginning of the recorded curve on the fitted base curve.

d) Find the last sample on the tail having a voltage value higher than 0.4 times the extreme value V_e, and discard data after that sample. This is to provide a consistent end point for the fitted base curve.

e) Find the base curve $V_m(t)$ by fitting the remaining samples to the following double exponential function:

$$u_d(t) = A\left(e^{\frac{(t-D)}{B}} - e^{\frac{(t-D)}{C}}\right) \tag{A.4}$$

where

t	is time
$u_d(t)$	is the double exponential voltage function
A, B, C, and D	are the parameters to be found by the fitting

NOTE—The voltage values and the time values may differ by over 10 orders of magnitude, which can result in divergence of the fitting calculation. Scaling the voltage values and time values to an approximately equal range helps to resolve the divergence problem. The fitted parameters A, B, C, and D need to be scaled back to their original scales once a fit is found.

f) Construct the base curve $V_m(t)$ by using the base level of the recorded curve for sample points up to time D (as defined in step d) and values of $u_d(t)$ for samples points from time D up to the instant of the last sample defined in step d. Find the peak voltage V_{mp} from the base curve $V_m(t)$.

g) Subtract the base curve, $V_m(t)$, from the recorded curve, $V(t)$, and obtain the residual curve:

$$R(t) = V(t) - V_m(t) \tag{A.5}$$

h) Construct the digital filter with its transfer function $H(f)$ equal to that defined by Equation (A.2).

i) Apply the digital filter to the residual curve $R(t)$ and obtain the filtered residual curve $R_f(t)$.

There are two algorithms (frequency domain and time domain algorithms) that can be used for this step.

In the frequency domain, perform a Fourier transform of $R(t)$ obtained from Equation (A.5) to obtain $R_i(f)$, and then apply the digital filter as follows:

$$R_0(f) = R_i(f) \times H(f) \tag{A.6}$$

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where:

$R_0(f)$ is the output voltage vector of the filter
$R_i(f)$ is the input voltage vector of the filter
$H(f)$ is the transfer function of the filter

Finally, convert $R_0(f)$ back to the time domain to obtain the filtered residual waveform $R_f(t)$.

In the time domain:

$$R_f(t) = \int_0^\infty R(t) \times H(t - f)df \tag{A.7}$$

where:

$R_f(t)$ is the filtered residual curve (output voltage of the filter)
$R(t)$ is the residual curve (input voltage of the filter) from Equation (A.4)
$H(t)$ is the time domain counterpart of $H(f)$

j) The filtered residual curve $R_f(t)$ is then added back to the base curve $V_m(t)$ to form the test voltage curve $V_t(t)$ for parameter calculation.

$$V_t(t) = V_m(t) + R_f(t) \tag{A.8}$$

Calculate the impulse test voltage, V_t, and time parameters using the test voltage curve.

k) Calculate the relative overshoot amplitude, which is defined as:

$$\beta'(\%) = 100\frac{V_e - V_{mp}}{V_e} \tag{A.9}$$

l) Display the recorded curve $V(t)$ and the test voltage curve $V_t(t)$.

m) Report the value of the test voltage V_t, front time T_1, time to half-value T_2, and relative overshoot amplitude β' (%).

A.2.3 Procedure for chopped lightning impulses

A.2.3.1 Front-chopped lightning impulses

The test voltage factor function shall not be applied to the front-chopped impulses. The test voltage curve for calculation of the test voltage and time-to-chopping is the recorded curve.

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A.2.3.2 Tail-chopped lightning impulses

The test voltage curve of a tail chopped impulse has to be obtained with the assistance of a recorded full lightning impulse produced by the same test circuit. The procedure described in A.2.2 cannot be directly applied to tail-chopped impulses since the fitting model function [Equation (A.4)] is not valid for a chopped impulse.

The tail-chopped lighting impulse may be produced intentionally as part of a standard test procedure such as a transformer impulse test. Tail-chopped impulses may also be produced when insulation under test fails. In these cases, full lightning impulses from the same test circuit are normally available prior to the first occurrence of a tail-chopped impulse. For example, during impulse testing of transformers, a reduced level lighting impulse is normally applied before the chopped impulse waves. In other insulation tests, full impulses of increasing magnitudes are applied until a disruptive discharge occurs. It is usual that the test circuit remains unchanged during the preliminary voltage applications and the chopped wave voltage applications, and, therefore, the prospective full waveform shape of the chopped impulse record would be the same as that of the preliminary applications, up to the time of the chop. The procedures described below in A.2.4 are based on this assumption.

A.2.4 Recommended steps for calculating parameters of tail-chopped impulses

A.2.4.1 Preferred method (voltage reduction ratio method)

a) Detect if a disruptive discharge has occurred during the last application of the impulse. If no, determine the full lightning impulse parameters using the steps given in A.2.2. If yes, go to the next step.

b) Detect if the disruptive discharge resulted in a front chopped impulse. If yes, report the occurrence of front chopped impulse and use the procedure described in A.2.3.1 to determine the parameters of the impulse. If no, go to the next step.

c) Retrieve the results of the last full lightning impulse applied in the test.

d) Find the voltage reduction ratio $R_v = V_t/V_e$ using the value of V_t and V_e of the full lightning impulse.

e) Find V_e of the tail-chopped impulse from its recorded curve.

f) Find the test voltage of the tail-chopped impulse by multiplying its V_e by R_v:

$$V_t(\text{chopped impulse}) = V_e(\text{chopped impulse}) \times R_v \quad \text{(A.10)}$$

g) Use the value of T_1 determined from the test voltage curve of the full lightning impulse (determined with the steps described in A.2.2) as the T_1 value of the chopped impulse.

h) Find the virtual origin O_1 of the chopped impulse as follows:

$$O_1 = t(30) - 0.3T_1 \quad \text{(A.11)}$$

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where:

$t(30)$ is the time when the recorded chopped impulse reached 30% of V_t

T_1 is the front time determined from step g

Then use O_1 to calculate the value of time to chopping T_c from the recorded chopped impulse curve.

i) Report the value of the test voltage V_t, front time T_1, time to chopping T_c, and relative overshoot amplitude β' (%).

A.2.4.2 Alternative method (tail patch method)

a) Detect if a disruptive discharge has occurred during the last application of the impulse. If no, determine the full lightning impulse parameters using the steps given in A.2.2. If yes, go to the next step.

b) Detect if the disruptive discharge resulted in a front chopped impulse. If yes, report the occurrence of front chopped impulse and use the procedure described in A.2.3.1 to determine the parameters of the impulse. If no, go to the next step.

c) Remove the portion of the chopped waveform record after the chop to obtain the portion prior to chopping.

d) Retrieve the recorded waveform of the last applied full lightning impulse.

e) Patch the portion prior to chopping, using a re-scaled tail of the recorded full lightning impulse, to obtain a tail patched impulse curve. This is achieved by scaling up (and, if necessary, by time shifting) the full lightning impulse waveform until the difference between the two waveforms is a minimum, up to the time of chop. The tail of the scaled full lightning impulse is then patched to the front portion obtained in step c.

f) Follow the steps given in A.2.2 to determine the test voltage curve from the tail patched impulse curve obtained in step e. Calculate the test voltage, relative overshoot amplitude, and front time from this test voltage curve.

g) Find the virtual origin O_1 of the chopped impulse curve using the test voltage curve determined in step f, and then find the value of time to chopping T_c from the recorded chopped impulse curve.

h) Display the recorded curve and the test voltage curve.

i) Report the value of the test voltage V_t, front time T_1, time to chopping T_c, and relative overshoot amplitude β' (%).

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A.3 Manual procedure for calculation from graphic waveforms

A.3.1 Description

This procedure is also an approximate implementation of Equation (A.1), and it is used for manual calculation of the impulse parameters from waveforms in a printed, displayed or any other graphic format [B41] [B85].

The procedure first requires drawing a base curve $V_m(t)$ manually through the recorded curve $V(t)$. The amplitude and frequency of the residual curve can then be determined from the difference between the peak voltage of $V(t)$ and the peak voltage of $V_m(t)$.

The frequency of the overshoot is determined from its period. The value of the voltage factor $k(f)$ is then determined from the formula in Equation (A.2). The test voltage is then calculated using Equation (A.1).

A.3.2 Steps for calculating lightning impulse parameters

The following steps are recommended for calculating the impulse parameters using this manual procedure:

a) Draw a base curve $V_m(t)$ through the recorded curve $V(t)$, and find its peak value V_{mp}.

b) Find the peak voltage V_e from the recorded waveform $V(t)$.

c) Calculate the duration t of the overshoot of the recorded curve by finding the time difference between the two crossing points of the $V(t)$ and $V_m(t)$ curves, just before and just after the maximum peak of $V(t)$, and calculate the overshoot frequency $f_0 = 1/(2t)$.

d) Calculate the value of the test voltage factor $k(f)$ using Equation (A.2) and the frequency f_0.

e) Calculate the test voltage V_t using Equation (A.1), and determine the time parameters from the base curve using V_t as the test voltage amplitude.

f) Calculate the relative overshoot amplitude $\beta'(\%) = 100 \times (V_e - V_{mp})/V_e$.

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Annex B

(informative)

Experimental step response measurements

This annex describes procedures for performing experimental step response measurements and determining the relevant response parameters from the response oscillograms obtained. The measurement of the experimental step response is a valuable method of characterizing and qualifying the dynamic behavior of an impulse voltage divider, an impulse oscilloscope, or a digital recorder.

The procedures given in this annex may be used:

a) As an alternative means of qualifying a reference measuring system for impulse voltages as described in 5.6.2.2.2, when direct comparison to a standard measuring system is not possible.
b) As a performance check to verify the correct function and approximate accuracy of an approved measuring system, as described in 8.5.4.
c) To verify the dynamic performance of the reference voltage divider described in 8.7.1.
d) To provide the measured step response as required when using the convolution method described in Annex C to estimate the errors in time parameter measurements.

B.1 Procedure for measuring the experimental step response

From the high-voltage input terminal of the measuring system, a conductor of the same diameter as the high-voltage lead of the measuring system is arranged to run vertically downward to a small step generator located at ground, as illustrated in Figure B.1. The step generator must have approximately zero impedance while generating the step and during the subsequent response, and is comprised of a high-speed switch that short circuits the two input terminals. The voltage step is generated by applying a voltage across the switch and then closing the switch. Suitable switches for the purpose are a mercury wetted relay, or a gap having a nearly uniform field (of about 1 mm spacing), which is caused to spark over. Large gaps are not satisfactory for an accurate determination because they neither have a sufficiently fast rate of change of voltage, nor do they have a sufficiently low impedance after sparkover.

A low direct voltage source connected through a current limiting resistor can be used with a mercury wetted relay. The output from the divider is readily measurable with general purpose analog and digital oscilloscopes, but may be too low to record with a high-voltage impulse oscilloscope. In this case, the impulse oscilloscope has to be substituted with another oscilloscope having adequate bandwidth and higher sensitivity to record the step response. This oscilloscope should have response characteristics similar to those of the impulse oscilloscope normally used, since otherwise erroneous information will be obtained about the behavior of the measuring system when measuring rapid rates of change of voltage. It is also important that the normal impedance to ground from the divider output and the normal cable arrangements be maintained when using this oscilloscope, especially when measuring the response of capacitive dividers.

If a gap having a nearly uniform field is used as the switch, an impulse having a front of 10 ns to 15 ns can be applied to the gap, the amplitude being adjusted to cause the gap to spark over at or near the crest of the voltage. For capacitor dividers or mixed dividers, direct or alternating voltages may be used. The sparkover voltage of the gap can be increased by increasing the air or gas pressure in the gap; this may eliminate the need for amplification and thus permit the use of the normal impulse oscilloscope.

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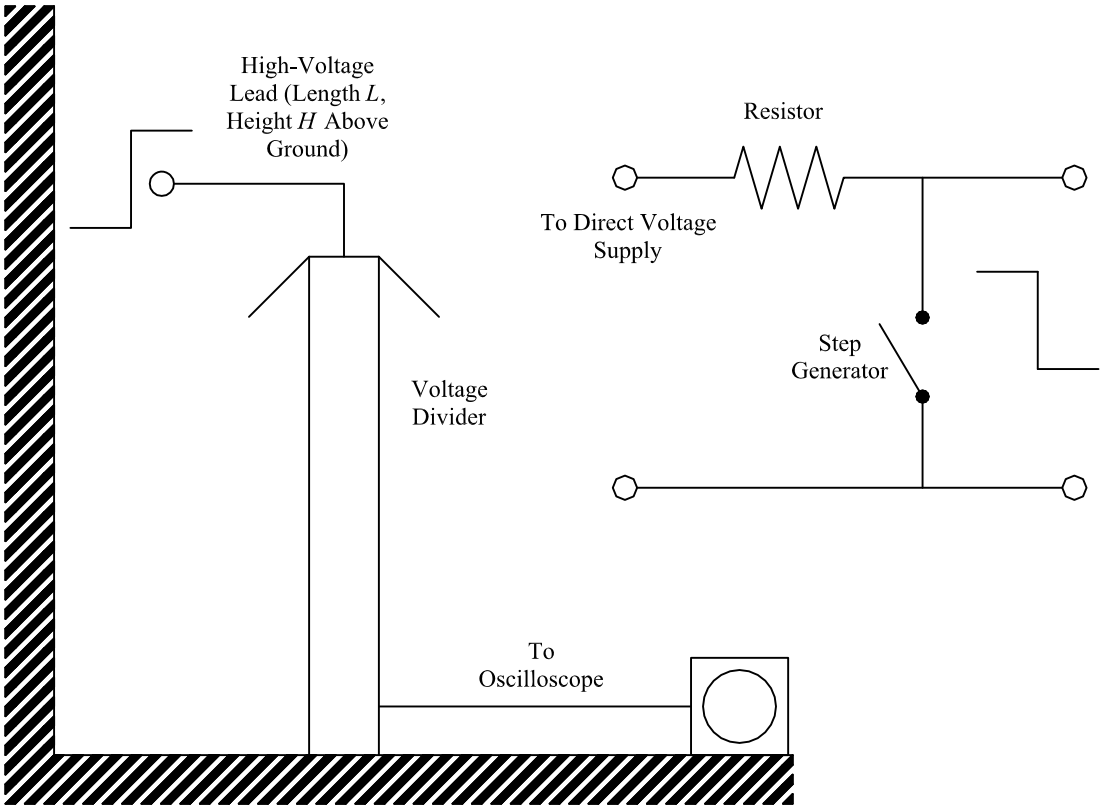


Figure B.1—The experimental step response method

It is recommended that the experimental procedure be carried out for several lengths of high-voltage lead covering the range that is likely to be used in practice.

It is also recommended that the response waveform be measured with several sweep rates to determine both the short-time response and the long-time step level.

B.2 Determination of the response parameters from experimental step response oscillograms

A typical normalized response record obtained by the experimental step response method is shown in Figure B.2.

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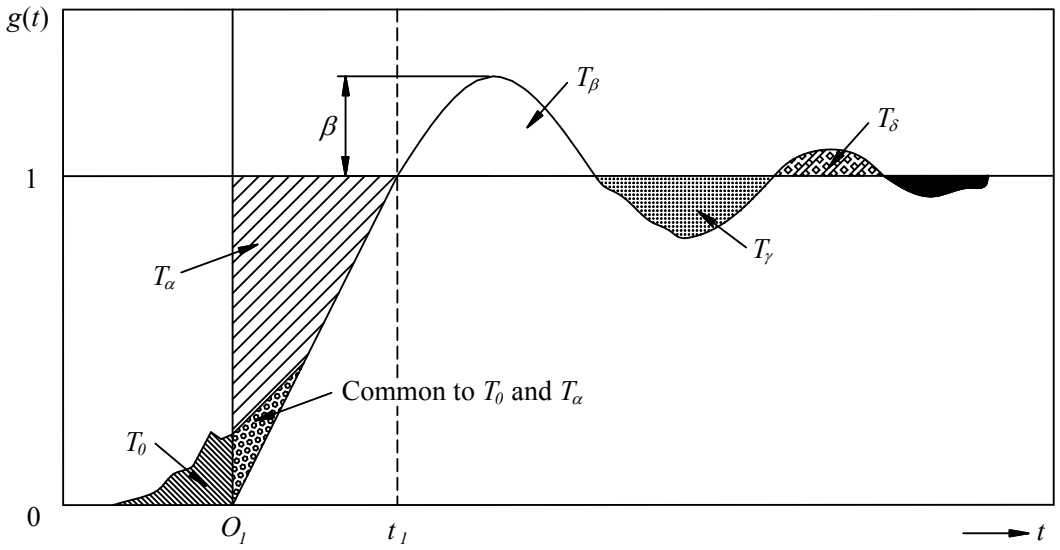


Figure B.2—Definitions of response parameters with respect to the normalized experimental step response *g*(*t*)

In order to establish the response parameter, a virtual origin (O_1) has to be determined. A procedure for doing this is given in B.2.1. This virtual origin is considered to be the starting point of the step response, and also of the signal to be measured in a practical test.

B.2.1 Determination of the virtual origin (O_1)

According to its historical definition, O_1 is the intersection with the time axis of a straight line drawn as a tangent to the steepest portion of the front of the response curve. Since there usually are noise and oscillations on a step response, it is very difficult to find "the steepest portion" with consistency commensurate with the accuracy requirements in evaluating response parameters. Depending on the situation, the uncertainty of partial response time caused by the wrong O_1 can be as large as 100% or more (see Annex D). The solution to this problem should consider two points. First, the noisy front part of the step response has to be smoothed before it is used for calculation. This standard permits, in the case of a response with oscillations on the front, a mean curve to be drawn through the oscillation and used to determine the tangent line. A piece-wise cubic spline smoothing algorithm is a suitable tool for this case. Second, the uncertainty of an interval between two points that are far away from each other, such as the 10% to the 90% points, will be smaller than that of a steepest tangent line on the front part. If the steepest part of a unit step response is close to or higher than its unit level, even a small error on the tangent line will produce a large error in O_1. The virtual origin may therefore be determined by the intersection of the time axis and a line that passes through the 10% and 90% points on the front.

B.2.2 Determination of the experimental response time (T_N)

The approximate step response time (T_N), known as the experimental response time, is found from:

$$T_N = T_\alpha - T_\beta + T_\gamma - \ldots\ldots \quad \text{(B.1)}$$

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where:

T_α, T_β, T_γ, … are the shaded areas shown in Figure B.2.

B.2.3 Determination of the settling time (t_s)

The settling time, t_s, is the shortest time for which the residual response time, $T_R(t)$, becomes and remains less than 2% of t. This statement may be expressed by Equation (B.2):

$$\left| \int_{t_s}^{\infty} [1 - g(t)]\, dt \right| < 0.02\, t_s \qquad \text{(B.2)}$$

and is also illustrated in Figure B.3.

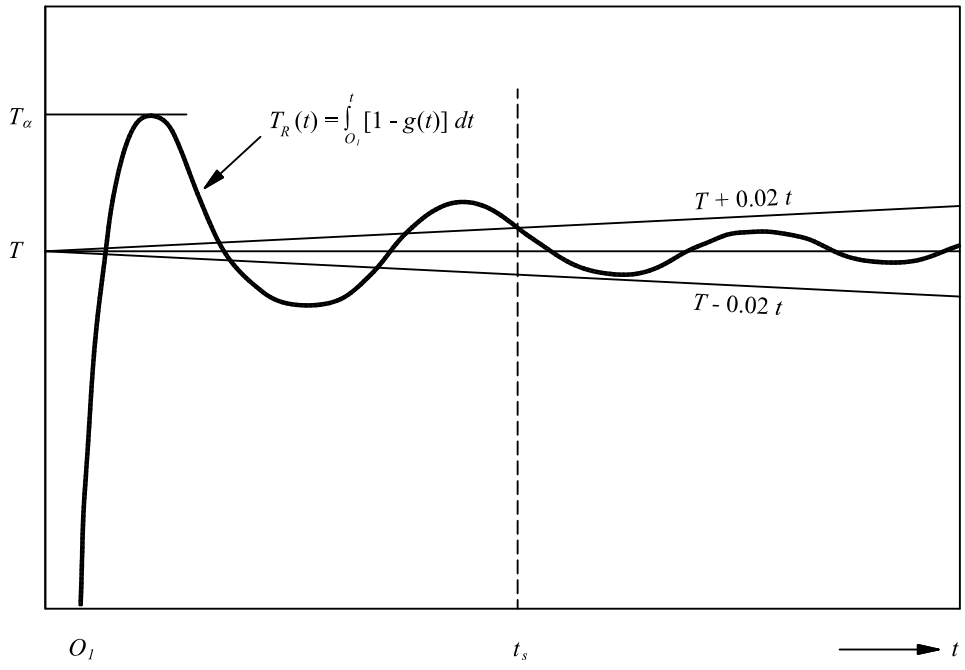


Figure B.3—Definitions of response parameters with respect to $T(t)$

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Annex C

(informative)

Convolution methods

The convolution method is used to evaluate the dynamic performance of an impulse voltage measuring system from its step responses (Annex B). It uses the step response to estimate the measuring system's output impulse waveform from the input impulse waveform. The differences of the impulse parameters of the output waveform relative to the input waveform may be used to estimate the performance of the measuring system for a particular waveform to be measured.

This technique can be used:

a) To estimate the response of the measuring system to a new waveform.

b) As a performance check to verify measuring system stability.

In general, this technique should not be used for correction of measured waveforms, since the actual input waveform is not known. This technique only gives a valid output for the assumed input. The calculated output waveform and its parameters can only be used as an estimate of the response of the measuring system to this assumed input.

The scale factor and linearity must be determined in separate tests in order to fully qualify the measurement system.

C.1 The convolution method

If the input impulse waveform and the unit (normalized) step response (Annex B) of an impulse measuring system are $V_{in}(t)$ and $g(t)$ respectively, the output, $V_{out}(t)$, may be expressed by the following convolution integral:

$$V_{out}(t) = \int_0^t V_{in}'(\tau) \times g(t-\tau) d\tau \qquad \text{(C.1)}$$

where:

t is time

$V_{in}'(t)$ is the first derivative of the input impulse voltage waveform $V_{in}(t)$

If $g(t)$ and $V_{in}(t)$ are sampled with the same sampling interval and the number of samples of $g(t)$ is the same as that of $V_{in}(t)$, the continuous convolution integral [Equation (C.1)] reduces to the causal form of the discrete convolution sum:

$$V_{out}(i) = \sum_{k=0}^{i} V_{in}'(k) \times g(i-k) \times \Delta t \quad \text{for } i = 0,\ 1,\ 2, \ldots, n\text{-}1 \qquad \text{(C.2)}$$

where:

$V_{out}(i)$ is the discrete output

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$V'_{in}(i)$ is the first derivative of input digital record

$g(i)$ is the unit step response digital record

n is the number of samples of the input digital record

Δt is the sampling interval of the input and output digital records, and the step response digital record

C.2 Procedure for performing the convolution calculation

This procedure is based on the discrete convolution sum described by Equation (C.2). It is used for computer-aided calculation using digital impulse waveforms. The procedure is used to estimate the differences of the impulse parameters of the output relative to the input waveforms of an impulse measuring system. The procedure given here describes the major steps of the calculation. These steps are:

a) Obtain the input impulse waveform digital record $V_{in}(i)$ for i = 0, 1, 2, …, n-1, and calculate its impulse parameters. The selected numerical input waveform $V_{in}(t)$ should be as close as possible to the waveform to be measured in the specific impulse tests. For example, if a chopped lightning impulse test is to be made, a chopped lightning impulse waveform is preferred rather than a full lightning impulse waveform. If a non-standard waveform is expected such as the ones occasionally seen in transformer impulse tests, a representative waveform is recommended as the input waveform instead of the standard full lightning waveform.

b) The sampling rate of the input impulse waveform should be identical to that of the unit step response, with the number of its samples equal to that of the unit step response (see step c). The input waveform should be a smooth waveform with the highest frequency of the noise having been reduced well below the Nyquist frequency (half of the sampling frequency of the impulse digital record). Alternatively, a smooth input waveform digital record and its impulse parameters may be derived from:

   1) An analytical expression of the impulse (e.g., a superposition of two ideal exponential functions). The impulse parameters of this waveform may be obtained either from the analytical expression or from the impulse calculation software of the impulse measuring system being examined. Or,
   2) A recorded real waveform, smoothed by a precision low pass digital filter or a piecewise cubic spline fitting algorithm. The impulse parameters of this waveform may be obtained from the impulse calculation software of the impulse measuring system being examined.

c) Obtain the first derivative $V'_{in}(i)$ for i = 0, 1, 2, …, n–1, of the input impulse waveform $V_{in}(i)$ by numerical derivation.

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d) Obtain the unit step response digital record *g(i)* for i = 1, 2, …, m-1 and $m = n + j$, where j is the number of data points before the origin of the recorded step response O_1 as follows:

1) Obtain the unit step response by normalizing the measured step response (Annex B). To obtain a low noise unit step response for convolution purposes, averaging several step response records or a piecewise cubic spline fitting algorithm may be used. The smoothness of the unit step response digital record $g(i)$ is less critical if Equation (C.2) is used for the convolution calculation and the impulse digital record $V_{in}(i)$ is already smooth.
2) Obtain the zero level, l_0, of the step response by averaging the samples of the recorded step response digital record $s(i)$ before the starting edge of the step.
3) Obtain the reference level, l_R, of the step response by averaging the samples of the recorded step response digital record $s(i)$ within a time range including the shortest front time for which the measuring system is to be used, and up to the time reflecting the frequency at which the scale factor of the converting device has been determined.
4) Normalize the step response digital record $s(i)$ into a temporary unit step response digital record, $g_0(i)$, by using the following formula:

$$g_0(i) = \frac{s(i) - l_0}{l_R - l_0} \tag{C.3}$$

5) Find the noise amplitude at the zero level by finding the standard deviation, d_0, of the samples of the $g_0(i)$ digital record before the start of the step. Searching backwards from the end of $g_0(i)$, find the sample with its value being higher than three times the standard deviation d_0. The time of this sample is assigned as the origin, O_1, of $g_0(i)$. Assign the index of this sample to j.
6) Construct the unit step response $g(t)$ from the origin by removing the samples of $g_0(i)$ before the origin

$$g(i - j) = g_0(i) \quad \text{for } i = j, ..., m + j - 1 \tag{C.4}$$

NOTE 1— Recorded $g_0(i)$ has $m + j$ points. Unit step response $g(i - j)$ has $n = m$ points after removing j points before the origin O_1.

NOTE 2— The digital recorder should have a sampling rate of at least 100 megasamples/s, an analog bandwidth of at least 100 MHz, and have 8 bits or higher resolution. The record length and sampling rate should be identical to that of the numerical input waveform used. If the record length is not as long as the numerical input waveform, the last portion of the unit step response waveform may be extrapolated by the points with unit amplitude.

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e) Obtain the output impulse waveform digital record and its impulse parameters as follows:

1) Obtain the output impulse waveform digital record $V_{out}(i)$ by calculation using Equation (C.2) either in the time domain or in the frequency domain.
2) Calculate the impulse parameters of $V_{out}(i)$ using the impulse calculation software of the impulse measuring system.
3) Calculate the difference between the impulse parameters of $V_{out}(i)$ and $V_{in}(i)$.

C.3 Verify linearity of the measurement system

The measurement system must be linear since convolution is based on linear system analysis. The linearity of the measurement system should be proven to meet the requirements of this standard, as defined in 8.5.

C.4 Use of the parameter differences

If the differences between input and output voltage peak or time parameters exceed the uncertainty requirements given in 8.3 of this standard, the system is inadequate for the measurement of the input waveform used in the calculations.

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Annex D

(informative)

Evaluation of measurement uncertainties

D.1 General

Any set of measurements is subject to uncertainty, and the establishment of uniform standard techniques for measurement and testing requires that the uncertainty of the measurement be controlled and known to within calculable limits. In general, the result of a measurement is only an approximation or estimate of the measurand, and thus the result is complete only when accompanied by a quantitative statement of its uncertainty. The uncertainty of a measurement result gives the boundary limits within which the "true" value of the measurand, within a given level of confidence, is expected to lie. To assess the uncertainty of a measurement, all contributions to this uncertainty have to be stated and included in an uncertainty budget for this measurement.

Since this is the case, it is customary to estimate what the uncertainty is by establishing limits on the measurement uncertainties through direct testing and familiarity with the behavior of the measurement system. This subclause describes the different types of uncertainties that occur in measurements and some of the methods for estimating the uncertainties of measurements in accordance with the ISO/IEC Guide 98-3, Uncertainty of measurement—Part 3: Guide to the expression of uncertainty in measurements (GUM) [B128]. Also included are some comments on and examples of their application to high-voltage measurements as defined by this standard.

D.2 Terms used in evaluation of uncertainty

standard uncertainty: Uncertainty of the result of a measurement expressed as a standard deviation.

type A uncertainty: Evaluated by the statistical analysis of series of measurements.

type B uncertainty: Evaluated by means other than statistical analysis of series of measurements.

combined standard uncertainty: Combination of the individual standard uncertainties, whether arising from Type A or Type B evaluations, using the square root of the sum of the squares of each contribution.

expanded uncertainty: An interval about the result of a measurement result within which the value of the measurand is believed to lie within a specific probability.

D.2.1 Type A evaluation of standard uncertainty

A Type A evaluation of standard uncertainty may be based on any valid statistical method for treating data. Examples are calculating the standard deviation of the mean of a series of independent observations.

These independent observations can be accomplished for the example of a voltage divider either by applying voltage n-times, or by taking n consecutive readings.

If the n independent observations $X_{i,k}$ of the input quantity X_i are obtained under the same measurement conditions, the estimate is usually the sample mean:

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$$\overline{X}_i = \frac{1}{n}\sum_{k=1}^{n} X_{i,k} \tag{D.1}$$

with the standard deviation $s(\overline{X}_i)$ of the uncorrected mean as the standard uncertainty $u(x_i)$ associated with the observations:

$$u(x_i) = s(\overline{X}_i) = \left(\frac{1}{n(n-1)} \sum_{k=1}^{n} (X_{i,k} - \overline{X}_i)^2 \right)^{1/2} \tag{D.2}$$

where:

n is the number of measurements

$X_{i,k}$ are the measured values for k = 1 to n

Typical sources of uncertainty include but are not limited to:

- Random fluctuation
- Changes in the output of a calibrator or other voltage source (input voltage fluctuation)
- Temperature of a calibration standard
- Uncertainty in discrimination
- Setting a pointer to a mark on a scale (parallax error)
- Interpolation between marked points on a scale (resolution error)

When calibrating a high-voltage measuring system or component, multiple measurements should be taken.

D.2.2 Type B evaluation of standard uncertainty

A Type B evaluation of standard uncertainty is usually based on scientific judgment using all the relevant information available, which may include:

- Previous measurement data
- Experience with, or general knowledge of, the behavior and property of relevant materials, instruments and reference standards, such as long-term and short-term stability
- Effects of environmental conditions
- Manufacturer's specifications, such as resolution
- Data provided in calibration and other reports,
- Uncertainties assigned to reference values taken from published data

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Once a measuring system (or a component) has been calibrated and is then used in a test, the uncertainty of the calibration is treated as one of the Type B contributions in the estimate of the overall uncertainty of the test result.

All known corrections should be applied to the calibration or measurement, and the uncertainties of these corrections should be included in the overall uncertainty budget.

Figure D.1 shows the most commonly used probability distribution functions and their standard deviations.

The uniform distribution, which assumes that all values of the quantity (or measurand) falling within the range set by the limits ± δ_i are equally probable, has a standard uncertainty $u(x_i)$ given by $\delta_i / \sqrt{3}$. It provides the most conservative estimate of the uncertainty (the maximum standard deviation) of the four distributions shown in the figure.

If the Type B uncertainty is normally distributed and limits of ± δ_i define the 95% probability interval, the standard deviation is then $\delta_i / 2$.

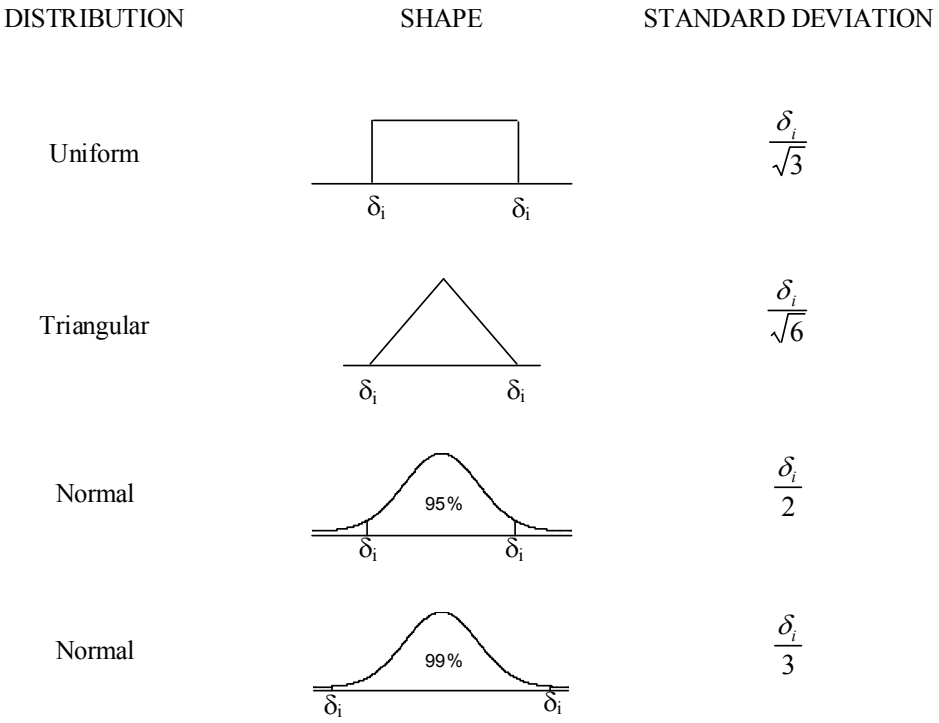


Figure D.1— Examples of four different probability distributions and their standard deviations

D.3 Combined standard uncertainty

Once the sources and values of Type B uncertainty have been determined, they need to be combined with the estimate of the Type A uncertainty into a single statement of combined standard uncertainty to obtain the estimated standard deviation of the result. The usual method for obtaining the combined standard uncertainty, also called the law of propagation of uncertainty, is described below.

When all the standard uncertainties of the input quantities have been determined, the combined standard uncertainty $u_c(y)$ can be calculated as follows:

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$$u_c(y) = \left(\sum_1^n u_i^2(y) \right)^{1/2} = \left(\sum_1^n c_i^2 u^2(x_i) \right)^{1/2} \quad \text{(D.3)}$$

where:

$u(x_i)$	is the standard uncertainty (either Type A or Type B) of input quantity x_i
c_i	is the sensitivity coefficient of the input quantity x_i
$u_i(y)$	is the standard uncertainty in the unit of measurand y obtained from the standard uncertainty of the input quantity x_i
n	is the total number of input quantities

The sensitivity coefficient, c_i, is the coefficient used to convert the uncertainty value of an input quantity, $u(x_i)$, to an uncertainty value, $u_i(y)$, in the unit of the measurand (see examples below in D.7).

The sensitivity coefficients may be obtained by calculation of the first partial derivatives of the measurand, y, with respect to the input quantity, x_i, either analytically [GUM Equation (11b) [B128]] or numerically, if the model function describing the relationship between the measurand and its input quantities has been established.

The sensitivity coefficient of an input quantity may also be determined by experiments (i.e., by observing the change of the measurand with a small change of the input quantity). In essence, the definition of sensitivity coefficient may be expressed in words as follows:

$$\textit{sensitivity coefficient of an input quantity} = \frac{\textit{change in the measurand}}{\textit{small change in the input quantity}}$$

D.4 Expanded uncertainty

To provide a level of confidence about the interval within which the value of the measurand is believed to lie, the expanded uncertainty is obtained by multiplying the combined standard uncertainty by a coverage factor k:

$$U = k \times u_c(y) \quad \text{(D.4)}$$

For an uncertainty budget established with sufficient degrees of freedom (normal distribution), a value of k equal to 2 provides a level of confidence of approximately 95%, whereas a value of k equal to 3 provides a level of confidence of approximately 99%.

D.5 Coverage factor and effective degrees of freedom

To determine the coverage factor, the effective degrees of freedom of the combined standard uncertainty is calculated as:

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$$V_{eff} = \frac{u_c{}^4(y)}{\sum_{i=1}^{N} \frac{u_i{}^4(y)}{v_i}} \quad \text{(D.5)}$$

with

$$V_{eff} \leq \sum_{i=1}^{N} v_i \quad \text{(D.6)}$$

where

v_i is the number of degrees of freedom of the individual standard uncertainty contribution, $u_i(y)$, to the combined standard uncertainty.

The number of degrees of freedom is a measure of the quality or reliability of the standard uncertainty. The number of degrees of freedom of a contribution to the uncertainty obtained by a Type A evaluation is usually the number of independent readings minus 1.

The number of degrees of freedom of an uncertainty contribution obtained by a Type B evaluation is discussed in D.5.1. The expanded uncertainty:

$$U = k \times u_c(y) = t_p(v_{eff}) \times u_c(y) \quad \text{(D.7)}$$

then provides an interval $Y = y \pm U_p$ having an approximate level of confidence p, where k is the coverage factor, which is obtained from the t-factor $t_p(v_{eff})$ of the t-distribution. Table D.1 gives the values of t_p at four different levels of confidence. For example, with an effective degrees of freedom value of 10, the t_p value (and hence the coverage factor k_p) is 2.23 at a level of confidence of 0.95 (or 95%).

To allow calculation by a computer program or spreadsheet, the following formula may be used to calculate t_p from v for a level of confidence of 95%:

$$t_p = 1.96 + \frac{2.374}{v} + \frac{2.818}{v^2} + \frac{2.547}{v^3} \quad \text{(D.8)}$$

The error of the above formula becomes insignificant when v is greater than 2. Similar formulae for other levels of confidence may be obtained by fitting their corresponding t_p values to a suitable mathematical model.

D.5.1 Degrees of freedom of Type B contributions

The numbers of degrees of freedom of all standard uncertainty contributions are required for determination of the effective degrees of freedom of the combined standard uncertainty from Equation (D.5). Questions arise as to how the number of degrees of freedom of a Type B standard uncertainty is determined.

One typical Type B uncertainty is the resolution of the measuring instrument. In this case, the number of degrees of freedom may be assumed to be close to infinity because the limits of the rectangular error distribution are precisely known.

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Table D.1—Value of $t_p(v)$

Degrees of freedom	Probability			
	0.68	**0.90**	**0.95**	**0.99**
1	1.84	6.31	12.7	63.7
2	1.32	2.92	4.30	9.92
3	1.20	2.35	3.18	5.84
4	1.14	2.13	2.78	4.60
5	1.11	2.02	2.57	4.03
6	1.09	1.94	2.45	3.71
7	1.08	1.89	2.36	3.50
8	1.07	1.86	2.31	3.36
9	1.06	1.83	2.26	3.25
10		1.81	2.23	3.17
30		1.70	2.04	2.75
100		1.66	1.98	2.63
Infinite		1.65	1.96	2.58

Another common Type B uncertainty is the uncertainty given in the calibration reports of instruments used in the measurement. If the uncertainty given in a calibration report is expressed as an expanded uncertainty at a certain level of confidence with a stated coverage factor, its number of degrees of freedom can then be determined from Table D.1. For calculation in a computer program or a spreadsheet, the following formula can be used to calculate the number of degrees of freedom v from a reported coverage factor k for a level of confidence of 95%:

$$v = 1 + \frac{2.392}{k - 1.96} - \frac{0.00076}{(k - 1.96)^2} \tag{D.9}$$

For most other Type B standard uncertainties, the correct degrees of freedom should be assessed on the basis of the quality of the uncertainty estimate as indicated by Equation (G.3) of GUM [B128]. A subjective assessment of the degrees of freedom can be made using the following formula, which is a modified version of Equation (G.3) of GUM [B128]:

$$v_i = \frac{5000}{(1 - C)^2} \tag{D.10}$$

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where

C is the percentage reliability (or certainty or confidence) of the estimation of the standard uncertainty.

For other distributions, refer to GUM [B128].

If the effective degrees of freedom are equal to or greater than 50, then there is no practical value in taking additional measurements.

D.6 Steps for calculating the expanded uncertainty

The steps for calculating the expanded measurement uncertainty are summarized as follows:

a) Establishing the model function of the measurand with respect to its input quantities if possible, and identify any other influence factors of the measurand that cannot be expressed in the model function.
b) Determining the sensitivity coefficients of the measurand with respect to its input quantities and influence factors, by either an analytical, numerical, or experimental method.
c) Determining the standard uncertainties of the input quantities and influence factors, by either Type A or Type B evaluation.
d) Determining or assigning numbers of degrees of freedom to the standard uncertainties.
e) Calculating the combined standard uncertainty of the measurand using Equation (D.3).
f) Calculating the effective degrees of freedom of the combined standard uncertainty using Equation (D.5).
g) Deciding the level of confidence for expressing the expanded uncertainty. The recommended level of confidence is 95%.
h) Determining the coverage factor using Table D.1 or Equation (D.8).
i) Calculating the expanded uncertainty by multiplying the combined standard uncertainty by the coverage factor [Equation (D.7)].

D.7 Examples of uncertainty limit evaluation

D.7.1 Example 1 – Uncertainty of the test voltage in an ac voltage withstand test

D.7.1.1 The measurement problem

A high-voltage disconnector with a rated voltage of 300 kV is type tested for its short duration power-frequency withstand voltage. The specified test voltage for the phase to earth insulation is 395 kV rms. The test voltage has to be corrected to the standard atmospheric conditions. The applied test voltage is measured

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with a high-voltage voltmeter in its peak detecting mode. The temperature, air pressure, and relative humidity of the laboratory are measured before and after the application of the test voltage.

D.7.1.2 Model function of the measurand

The evaluation of the uncertainty for the test voltage should start, according to GUM [B128], with formulating the mathematical model for the measurand, which is the applied test voltage here. An expression of the applied test voltage may be written as:

$$V_t = K_t\left(t, p, h, L, V_{50}\right) \times V_0 \tag{D.11}$$

where

V_t is the applied test voltage corrected to standard atmospheric conditions.

$K_t(t, p, h, L, V_{50})$ is the atmospheric correction factor (ACF) defined in this standard, which is a function of temperature t, absolute humidity h, air pressure p, discharge length of the insulation L, and the 50% probability breakdown voltage (peak) of the insulation V_{50}. V_0 is the specified test voltage, which is 395 kV rms in this case.

Vt here is the final measurand (i.e., the quantity to be measured), whereas $K_t(t, p, h, L, V_{50})$ and V_0 are the input quantities of V_t.

An input quantity may be a measurand in its own right, with its own input quantities. For instance, $K_t(t, p, h, L, V_{50})$ itself may be regarded as a measurand, with t, p, h, L, and V_{50} as its input quantities.

It should be noted that a mathematical model of a measurand (see Section 1.2 and Section D.1 of GUM[B128]) is particular to a particular measurement. The measurand is defined for a certain set of physical states and conditions. For instance, if the ambient temperature has a known effect on the voltmeter reading V_m, a model for V_m and hence for V_t may be then considered to reflect this temperature effect.

A mathematical model for a particular measurand cannot always be found. Sometimes the mathematical (or numerical) relationship between a measurand and the influence quantity is unknown. In such cases, the uncertainty contributions of the influence factors would have to be considered outside the mathematical model. In the case of the effect of proximity of other objects on the voltmeter reading, if no curve of the proximity effect but only an estimate of the effect is available, the proximity effect can be considered as an influence factor in the uncertainty estimation of the voltmeter reading, although the mathematical model of the effect is not known.

D.7.1.3 Sensitivity coefficients

The purpose of establishing a model for uncertainty analysis is to provide a mathematical basis for conversion of the uncertainty values of the input quantities to components of uncertainty in the unit of the measurand. In this example, the measurement uncertainties in such parameters as temperature t (in °C), pressure p (in kPa) and humidity h (in g/m3) will result in uncertainties in the atmospheric correction factor, and hence in the applied test voltage V_t, and therefore need to be converted to components of V_t (in kV) so that effects of these uncertainties on the uncertainty of V_t can be evaluated. The conversion is achieved by multiplying the sensitivity coefficients of the input quantities by their corresponding uncertainty values [see Equation (11a) and Equation (D.3) in GUM[B128]].

The sensitivity coefficients, c_i, may be obtained by calculation of the first partial derivatives of the measurand with respect to the input quantities, either analytically [See Equation (11b) in GUM [B128]] or

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numerically. In this example, the mathematical expression for $K_t(t, p, h, L, V_{50})$ is a quite complex one (see 13 in this standard). Therefore, obtaining sensitivity coefficients of t, p, h, L, and V_{50} by analytical calculation of the partial derivatives would be difficult if not impossible. However, the partial derivatives can be calculated numerically.

In this example, the sensitivity coefficients with respect to the ACF are calculated in a spreadsheet. Since the sensitivity coefficients of t, p, h, L, and V_{50}, that is, the partial derivatives

$$\frac{\partial K(t,p,h,L,V_{50})}{\partial t}, \frac{\partial K(t,p,h,L,V_{50})}{\partial p}, \frac{\partial K(t,p,h,L,V_{50})}{\partial h}, \frac{\partial K(t,p,h,L,V_{50})}{\partial L} \text{ and } \frac{\partial K(t,p,h,L,V_{50})}{\partial U_{50}}$$

are not constants but functions of t, p, h, L, and V_{50}, they will have to be calculated at the local values measured during the test. A partial derivative with respect to one particular parameter is calculated with its value being changed around its measured value while keeping the values of the other parameters constant at their measured values.

The sensitivity coefficients for V_t are then obtained by multiplying the sensitivity coefficients of K_t by V_0 according to Equation (D.11).

For example, to determine the sensitivity coefficient of K_t with respect to the air temperature t, the values of K_t are calculated with the values of p, h, L, and V_{50} being kept constant at their measured or estimated values and varying the values of t around its measured value. The sensitivity coefficient is then calculated as the ratio of the change in K_t values and the change in t values. In this example, the relevant measured or estimated values are as follows:

$t = 25.4$ °C

$p = 100.25$ kPa

$h = 8.21$ g/m^3

$L = 2.57$ m

$V_{50} = 1.1 \times \sqrt{2} \times 395 = 614.48$ kV

Using the above measured values for p, h, L, and V_{50}, K_t values calculated at temperatures 25.3 °C, 25.4 °C, and 25.5 °C are 0.988 345 3, 0.988 409 3, and 0.988 473 9 respectively. The corresponding sensitivity coefficients are then calculated as:

$(0.988\,409\,3 - 0.988\,345\,3)/(25.4 - 25.3) = 0.000\,640$ [1/°C]

$(0.988\,473\,9 - 0.988\,409\,3)/(25.5 - 25.4) = 0.000\,646$ [1/°C]

Of course, the calculation of the K_t values and the sensitivity coefficients may all be made in a spreadsheet or a computer program.

The sensitivity coefficient of K_t with respect to t at the measurement point 25.4 °C can be taken as the average of the two values, which gives 0.000 643. The sensitivity coefficient of the test voltage V_t with respect to t is then calculated as:

$$\frac{\partial V_t}{\partial t} = \frac{\partial (K_t \times V_0)}{\partial t} = V_0 \frac{\partial K_t}{\partial t} = 395 \times 0.000\,643 = 0.253\,98\,[\text{kV/°C}]$$

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The sensitivity coefficients with respect to p, h, L, and V_{50} may be calculated in the similar manner. As for influence factors of V_t, it is assumed that the mathematical model is unknown in this case, only the estimated uncertainty contributions of the shown factors to the voltmeter readings are available. Since these uncertainty values (discussed in the next section) are expressed directly in terms of the voltage reading, their c_i values for V_t would be unity without any dimension.

Table D.2 lists the sensitivity coefficients of all the input quantities and influence factors. Their uncertainty values and corresponding degrees of freedom are discussed in the next section.

Table D.2—Sensitivity coefficients c_i for V_t

Influence factors of uncertainty		Measured local mean values of the influence factors	c_i
Factors related to the determination of atmospheric correction factor, K_t	x_1, Ambient temperature	25.4 °C	0.253 98 kV/°C
	x_2, Ambient absolute humidity	8.21 g/m^3	1.123 kV/(g/m^3)
	x_3, Air pressure	100.25 kPa	0.7882 kV/kPa
	x_4, Discharge length	2.57 m	4.6789 kV/m
	x_5, 50% disruptive-discharge voltage	$1.1 \times \sqrt{2} \times 395 = 614.48$ kV	–0.019 64
Factors related to the ac high-voltage voltmeter reading, V_t	x_6, ac voltmeter calibration at 200 kV	–	1
	x_7, Voltmeter reading resolution	–	1
	x_8, Drift of voltmeter calibration with time	–	1
	x_9, Temperature effect on the voltmeter	–	1
	x_{10}, Voltmeter voltage non-linearity	–	1

D.7.1.4 Standard uncertainties and degrees of freedom

D.7.1.4.1 Uncertainty components of the atmospheric correction factor (ACF)

The section below describes the uncertainty components of the atmospheric correction factor K_t, which are all assumed to have a rectangular distribution.

Uncertainty of test object temperature, x_1

A semi-range a_1 = 2.0 °C uncertainty of rectangular distribution is assigned to the determination of the temperature around the test object. The standard uncertainty $u(x_1)$ is then:

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$$u(x_1) = 2.0 / \sqrt{3} = 1.155 \ ^\circ\text{C}$$

This component is mainly due to the uneven spatial distribution of temperature in the large high-voltage test hall and therefore a degree of freedom of $v_1 = 4$ is assigned. The uncertainty of the temperature measurement sensor also contributes to the temperature uncertainty of the test object.

Uncertainty of test object humidity, x_2

The semi-range $a_2 = 1.3$ g/m^3 uncertainty for absolute humidity includes the humidity sensor uncertainty, the change of humidity from the time of the humidity measured and the time of the test performed, because the humidity is changing due to a weather change at the time of the test. The standard uncertainty $u(x_2)$ is then:

$$u(x_2) = 1.3 / \sqrt{3} = 0.751 \ \text{g/m}^3$$

A degree of freedom of $v_2 = 4$ is also assigned to this component due to the relatively low reliability of the estimate.

Uncertainty of air pressure around the test object, x_3

The electronic barometric pressure sensor has a non-linearity of 0.1 kPa in the range of 97 kPa to 102 kPa, with a calibration uncertainty of the correction of 0.05 kPa. The correction is applied for the pressure reading of the sensor, while the non-linearity is considered as part of the uncertainty. The other source of uncertainty is the height difference between the location of the sensor and the location of the insulation being tested. An air pressure change of 0.02 kPa/m near sea level exists under the normal atmospheric conditions. An uncertainty component of 0.05 kPa due to a height difference of 3 m is also included. The air pressure change before and after the test is 0.15 kPa. Therefore a total estimated semi-range uncertainty is $a_3 = 0.35$ kPa, and the standard uncertainty $u(x_3)$ is:

$$u(x_3) = 0.35 / \sqrt{3} = 0.202 \ \text{kPa}$$

A degree of freedom of $v_3 = 8$ is assigned to this component due to the reasonable reliability of the estimates.

Uncertainty in the length of the discharge path the test object, x_4

The length of discharge path across the open gap is measured to be 2.22 m. The estimated semi-range uncertainty is $a_4 = 0.02$ m because the uncertainty of the exact discharge locations at the terminals. The corresponding standard uncertainty u(x_4) is:

$$u(x_4) = 0.02 / \sqrt{3} = 0.0116 \ \text{m}$$

A degree of freedom of $v_4 = 6$ is assigned to this component.

Uncertainty in the 50% disruptive discharge voltage V_{50}, x_5

Parameter V_{50} enters the calculation of K_t. Since the exact V_{50} value is unknown for voltage withstand tests, the V_{50} value is approximated, according to this standard, by using the standard test peak voltage $\left(\sqrt{2} \cdot 395 \ \text{kV}\right)$ multiplied by 1.1. Calculations have shown that under the normal ambient conditions at around the sea level, the maximum error in the choice of V_{50} without using an iterative procedure is 3%. The confidence in this error magnitude for the specific conditions of the test is quite low due to lack of

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further calculation, therefore a degree of freedom of $v_5 = 3$ is assigned for a Type B semi-range uncertainty of $a_5 = 3\%$ (or 18.43 kV) for this component. The standard uncertainty $u(x_5)$ is:

$$u(x_5) = 18.43 / \sqrt{3} = 10.64 \text{ kV}$$

D.7.1.4.2 Uncertainty components of the high-voltage voltmeter reading

Calibration uncertainty of the ac high-voltage voltmeter

The voltmeter was calibrated by a high-voltage calibration laboratory. The calibration report gives a calibrated reading correction at 200 kV with a relative expanded uncertainty $U(\%)$ of 0.2% with a level of confidence of 95% and a stated coverage factor k of 2.1. The report also gives the non-linearity test results, which are the percentage deviations of voltmeter readings from the corresponding values of a fitted linear line of six readings against readings of another approved high-voltage divider. The maximum of the six deviation values is 0.8%.

The correction has been applied to the voltmeter reading in obtaining the value of test voltage reading of V_t.

The combined standard uncertainty of the calibration at 200 kV stated in the calibration report now becomes a standard uncertainty of the voltmeter reading as an uncertainty component of the test voltage. The combined standard uncertainty of the calibration is simply the reported absolute expanded uncertainty U, which is $U(\%)$ / 100, divided by the stated coverage factor k. Let this uncertainty component be x_6 and its standard uncertainty be $u(x_6)$, then:

$$u(x_6) = \frac{U(\%) \times V_t}{100} \times \frac{1}{k_p}$$

$$= \frac{U(\%) \times K_t \times V_0}{100} \times \frac{1}{k_p}$$

$$= \frac{0.2 \times 0.9884 \times 395}{100} \times \frac{1}{2.1} kV$$

$$= 0.3718 \text{ kV}$$

Note that the calculated atmospheric correction factor is 0.9884 with the measured conditions at the time of the test. The corrected test voltage, V_t, is $0.9884 \times 395 = 390.4$ kV.

The number of degrees of freedom for this component, denoted as v_6, obtained from Table D.1 corresponding to a coverage factor k value (t_p value in the table) of 2.1 at the level of confidence (p value in the table) of 95% is 18. Therefore $v_6 = 18$.

Equation (D.9) can also be used for calculation of v values from given values of k at the level of confidence of 95%. The number of degrees of freedom v_6 calculated using Equation (D.9) is 18.047, which is in good agreement with value obtained from Table D.1.

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Reading resolution of the ac high-voltage voltmeter

The scale of the analog voltmeter is 6 kV/division in the range being used (600 kV). Visual reading of half of the division is possible with quite high reliability. This component can be considered as a Type B uncertainty of a rectangular distribution with the semi-range uncertainty $a_7 = 3/2 = 1.5$ kV, which give a standard uncertainty, $u(x_7)$, of:

$$u(x_7) = 1.5 / \sqrt{3} = 0.866 \text{ kV}$$

The assigned number of degrees of freedom $v_7 = 20$ because of the high but not perfect reliability (or confidence) in reading a half of the scale division.

Drift of the calibration of the high-voltage voltmeter

A drift in the voltmeter correction over time since the last calibration is estimated as a Type B component of rectangular distribution (approximately) to be $a_8 = 0.1\%$ (or 0.390 kV for the test voltage of 0.9884×395 kV), which gives a standard uncertainty, $u(x_8)$, of:

$$u(x_8) = 0.390 / \sqrt{3} = 0.225 \text{ kV}$$

Since the estimate is based on the results of two previous calibrations, the estimate would have reasonable level of reliability, so a number of degrees of freedom $v_8 = 8$ is assigned to this component.

Temperature effect on the high-voltage voltmeter

The mean ambient temperature during the test is 25.4 °C, while last calibration of the voltmeter was performed at 23 °C. The voltmeter manufacturer's specification of the temperature coefficient is 1% per 10 °C change in the temperature range of 10 °C to 30 °C. Therefore, a Type B semi-range uncertainty due to the difference between the temperature of use and that of the calibration is estimated as $a_9 = 0.1\%$ (or 0.390 kV), which also gives a standard uncertainty, $u(x_9)$, of:

$$u(x_9) = 0.390 / \sqrt{3} = 0.225 \text{ kV}$$

Since the precise temperature dependence of the voltmeter correction is unknown and because of the uncertainties in the measurement of the calibration temperature and the test ambient temperature, only a low number of degrees of freedom can be assigned to this component (i.e., $v_9 = 4$).

Voltage non-linearity of the high-voltage voltmeter

Voltage non-linearity test results are given in the report of the last calibration of the voltmeter. The report states a 0.8% maximum deviation of the voltage reading from the fitted linear line of six test voltage levels. The measured maximum deviation can be considered as a Type B component with a rectangular distribution. Therefore, $a_{10} = 0.8\%$ (or 3.12 kV), which gives a standard uncertainty, $u(x_{10})$, of:

$$u(x_{10}) = 3.123 / \sqrt{3} = 1.803 \text{ kV}$$

The degrees of freedom of this component can be determined by the following formula (see Chapter 4 of [B87]):

$$v = n - 1 - m \qquad \text{(D.12)}$$

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where

n is the number of points used for the fit

m is the order of the fit. For a linear fit, $m = 1$.

Therefore, $v_{10} = 6 - 1 - 1 = 4$.

D.7.1.5 Uncertainty table and combined standard uncertainty

The uncertainty components described in D.7.1.4 are summarized in Table D.3. The sensitivity coefficients are copied from Table D.2. The standard uncertainties in the unit of the measurand, $u_i(y)$, are obtained by multiplying the standard uncertainties of the input quantities and the influence factors, $u(x_i)$, by their corresponding sensitivity coefficients, c_i.

Table D.3—Standard uncertainties and degrees of freedom

Component x_i	Standard uncertainty of the input quantities and influence factors $u(x_i)$	Sensitivity coefficients c_i	Standard uncertainty of the measurand $\|u_i(y)\| = \| c_i u(x_i) \|$ [kV]	Degrees of freedom v_i
x_1	1.155 °C	0.253 98 kV/°C	0.2933	4
x_2	0.751 g/m^3	1.1235 kV/(g/m^3)	0.843	4
x_3	0.202 kPa	0.7882 kV/kPa	0.1593	8
x_4	0.0116 m	4.6789 kV/m	0.0540	6
x_5	10.64 kV	–0.019 64	0.2091	3
x_6	0.3718 kV	1	0.3718	18
x_7	0.866 kV	1	0.866	20
x_8	0.225 kV	1	0.225	8
x_9	0.225 kV	1	0.225	4
x_{10}	1.803 kV	1	1.803	4

The next step is to calculate the combined standard uncertainty of the test voltage, $u_c(y)$, and the effective degrees of freedom of the combined standard uncertainty.

The combined standard uncertainty, calculated using Equation (D.3) and values in Table D.4 is:

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$$u_c(y) = \left(\sum_1^n u_i^{\,2}(y) \right)^{1/2} = \left(\sum_1^n c_i^{\,2} u^2(x_i) \right)^{1/2}$$

$$= \sqrt{0.2933^2 + 0.843^2 + 0.1592^2 + 0.054^2 + 0.2091^2 + 0.3718^2 + 0.866^2 + 0.225^2 + 0.225^2 + 1.803^2}$$

$$= 2.26\,\text{kV}$$

The number of effective degrees of freedom calculated using Equation (D.5) and values in Table D.4 is:

$$V_{eff} = \frac{u_c^{\,4}(y)}{\sum_{i=1}^{N} \frac{u_i^{\,4}(y)}{v_i}}$$

$$= \frac{2.26^4}{\frac{0.2933^4}{4} + \frac{0.843^4}{4} + \frac{0.1593^4}{8} + \frac{0.054^4}{6} + \frac{0.2091^4}{3} + \frac{0.3718^4}{18} + \frac{0.866^4}{20} + \frac{0.225^4}{8} + \frac{0.225^4}{4} + \frac{1.803^4}{4}}$$

$$= 9.32$$

Table D.4—Results of calibration at 190 kV

Readings of reference voltmeter, V_r (kV)	Readings of test voltmeter, V_t (kV)	Relative correction (as % of test voltmeter reading) (%)
190.52	190.71	–0.100
190.58	190.76	–0.094
190.49	190.57	–0.042
190.48	190.63	-0.079
190.58	190.55	0.016
190.62	190.69	–0.037
Mean correction C_t (as % of mean test voltmeter reading)		–0.06
ESDM of C_t (as % of mean test voltmeter reading)		0.018
Degrees of freedom		5

D.7.1.6 Expanded uncertainty and coverage factor

According to the requirements of this standard, the expanded uncertainty having a level of confidence of 95% is to be reported for the test voltage. The expanded uncertainty is obtained by using Equation (D.7) [i.e., by multiplying the combined standard uncertainty, $u_c(y)$, with the coverage factor, k, for a level of confidence of 95%]. The coverage factor, k, obtained either from Table D.1 or by using Equation (D.8), with 9.11 effective degrees of freedom is:

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$k = 2.25$

The expanded uncertainty, U_p, is then:

$$U_p = k \times u_c(y) = 2.25 \times 2.26\,\text{kV} = 5.1\,\text{kV}$$

By taking appropriate rounding, the reported expanded uncertainty having a level of confidence of 95% would be 5 kV with a coverage factor of 2.3.

The test voltage may be stated in the test report as:

The applied test voltage, which is corrected with an atmospheric correction factor of 0.9884, is

$V_t = 390 \pm 5\,\text{kV}$ ($k = 2.3$).

D.7.2 Example 2 – Uncertainty of calibration of an ac voltmeter correction factor

D.7.2.1 The measurement problem

An ac voltmeter is calibrated against a reference voltmeter for its readings of 60 Hz RMS values in the range of 20 to 200 kV. The measurand of the calibration is the relative correction for correcting the readings of the voltmeter under test. The correction is measured at 23˚C, and is to be valid for spatial arrangements where the distances between the voltmeter and any earthed objects are at least the height of the voltmeter, which is 0.7 m.

The percentage correction C_t of the voltmeter under test is expressed as:

$$C_t(\%) = \frac{V_r - V_t}{V_t} \times 100 \qquad \text{(D.13)}$$

where

V_r is the voltage reading of the reference voltmeter

V_t the voltage reading of the voltmeter under test

If Equation (D.13) is taken as the mathematical model of the measurand C_t, its uncertainty can be estimated from the uncertainties of its input quantities in the model, which are V_r and V_t.

D.7.2.2 Sensitivity coefficients of a relative measurand

Since C_t is a relative quantity, for the purpose of calculation of its uncertainty, it would be most convenient for its sensitivity coefficients to be expressed in relation to the relative changes of its input quantities. From Equation (D.13), the sensitivity coefficients of C_t (%) with respect to the relative changes of V_r and V_t can be determined as follows:

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The changes of C_t with respect to V_r and V_t are:

$$\frac{\partial C_t}{\partial V_r} = 100\frac{1}{V_t}$$

and

$$\frac{\partial C_t}{\partial V_t} = -100\frac{V_r}{{V_t}^2}$$

respectively.

The sensitivity coefficients of C_t with respect to the relative changes of its input quantities

$$100 \times \frac{\partial V_r}{V_r}$$

and

$$100 \times \frac{\partial V_t}{V_t}$$

are:

$$\frac{\partial C_t}{100 \times \partial V_r / V_r} = \frac{V_r}{V_t} \quad \text{(D.14)}$$

and

$$\frac{\partial C_t}{100 \times \partial V_t / V_t} = -\frac{V_r}{V_t} \quad \text{(D.15)}$$

respectively.

Since the error in V_t is small in this case (see sections below), V_r and V_t are therefore approximately equal. Therefore the sensitivity coefficient with respect to relative change of V_r is approximately 1 [Equation (D.14)] and the sensitivity coefficient with respective to relative change of V_t is approximately -1 [Equation (D.15)]. This simplification is valid for all cases of voltmeter calibrations where the errors (or corrections) in the devices under test are less than 3%.

Equation (D.14) and Equation (D.15) indicate that absolute values of the sensitivity coefficients are higher than 1 if the error in V_t is negative (V_t is lower than V_r), but lower than 1 if the error in V_t is positive (V_t is higher than V_r). If V_t is 10% lower than V_r, from Equation (D.14) and Equation (D.15), the sensitivity coefficients would be 1.1 and -1.1 respectively.

Of course, the V_r and V_t themselves may be expressed as functions of other input quantities and their sensitivity coefficients with respect to these input quantities would have to be determined separately. The above analysis only applies to calculation of standard uncertainties of C_t from the standard uncertainties of V_r and V_t.

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D.7.2.3 Measurement at the reference voltage of 190 kV

The correction is first measured at a reference voltage level of 190 kV with other objects and walls being kept away from the voltmeter by at least 5 times its height. The ambient temperature is measured as 23 °C with a standard uncertainty of 0.5 °C.

Indicated values of the reference voltmeter and the voltmeter under test (also referred to as test voltmeter below) are read simultaneously six times. The results are shown in Table D.4.

The experimental standard deviation of the mean (ESDM) of C_t is a type A standard uncertainty contribution to the combined uncertainty of C_t. Since the ESDM of C_t in Table D.4 is expressed in the units of C_t (i.e., as a percentage of the reading of the test voltmeter), the sensitivity coefficient of this contribution will be 1.

D.7.2.4 Uncertainty contribution due to voltage non-linearity of the test voltmeter

The correction of the test voltmeter is not measured over its whole operating range, but at the single voltage level of 190 kV. In addition, the uncertainty of correction due to voltage non-linearity over the whole voltage range is estimated by a non-linearity test. Provision of a single correction value provides convenience for the subsequent use of the voltmeter, although the uncertainty of this correction would be larger than uncertainty values of corrections measured at individual voltage levels. Provision of correction values at different voltage levels covering the operating range would normally give lower uncertainty values in the subsequent use of the voltmeter, especially if interpolation of the corrections may be shown to be valid. However, this approach is normally less convenient for the subsequent use of the device because different correction values have to be used for different voltages.

The choice of these two approaches also depends on a range of other issues, which are outside the discussion here. In this case, the user has requested the approach of a single correction value because results of previous calibrations show that the uncertainty of a single value correction would be sufficiently low for the use of the voltmeter.

In this particular calibration, six voltages in the range of 20 kV to 200 kV are measured simultaneously by the test voltmeter and the reference voltmeter. The measured values and corresponding correction values are given in Table D.5. The deviation of the correction value, dC_t (%) in column 4, is the difference between the C_t value measured in this linearity test and the C_t value measured at the calibration voltage of 190 kV, which was –0.06 (Table D.4), that is,

$$dC_t(\%) = [C_t - (-0.06)](\%) \tag{D.16}$$

A Type B uncertainty contribution due to the voltage non-linearity is then approximated with the maximum dC_t value, 0.42%, as the semi-range value of a rectangular distribution. The standard uncertainty of this contribution is therefore:

$$0.42\,\% / \sqrt{3} = 0.242\ \%$$

Its number of degrees of freedom is estimated with number of measurement voltage points minus 1, that is:

$$6 - 1 = 5$$

The sensitivity coefficient is 1, because dC_t is already expressed in the units of C_t.

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Table D.5—Results of linearity test

Readings of reference voltmeter, V_r (kV)	Readings of test voltmeter, V_t (kV)	Correction, C_t (%)	dC_t (%)
20.38	20.46	–0.39	–0.33
65.00	65.42	–0.31	–0.25
110.75	111.58	–0.48	–0.42
155.45	156.67	–0.12	–0.06
197.15	198.84	–0.25	–0.19
20.38	20.46	–0.39	–0.33

D.7.2.5 Uncertainty contribution due to the proximity effect

The proximity effect is estimated from the difference between the correction with no nearby objects (result in Table D.4) and correction measured with earthed metallic fences being placed 0.7 m away from the test voltmeter. The measured mean correction with nearby fences in place is –0.26 %. The semi-range uncertainty of a rectangular distributed Type B uncertainty component due to proximity effect is then determined as:

$$dC_t(\%) = -0.06 - (-0.26) = 0.20\%$$

The corresponding standard uncertainty is:

$$0.2/\sqrt{3} = 0.1155\%$$

The degrees of freedom of this component is approximated from the number of readings of the mean correction values minus 1, that is:

$$6 - 1 = 5$$

D.7.2.6 Uncertainty of the reference voltmeter reading

The expanded uncertainty of the reference voltmeter reading from its calibration report is 0.25% with a coverage factor of 2.1 and a level of confidence of 95%.

The standard uncertainty is then:

$$0.25/2.1 = 0.119\%$$

Its degrees of freedom obtained by Equation (D.9) is 18.

According to Equation (D.14), the sensitivity coefficient would be approximately 1.

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D.7.2.7 Deviation of the reference voltmeter reading due to temperature

The temperature coefficient of the scale factor of the reference voltmeter measured in a performance test five years ago was + 0.05% / °C. The ambient temperature of its last valid calibration was 21.0 °C. Since the reference voltmeter is now used at 23 °C, the reference voltmeter reading would be in error due to this temperature difference. Instead of correcting the reference voltmeter reading using the temperature coefficient, a Type B uncertainty component of rectangular distribution is instead estimated without applying this small correction. The semi-range uncertainty of this component would be:

$$[0.05\ \%/\ ^\circ\mathrm{C}]\times 2^\circ\mathrm{C} = 0.1\%$$

which is the relative uncertainty of the reference voltmeter reading. According to Equation (D.14), the sensitivity coefficient for converting it to the component of C_t would again be approximately 1.

The standard uncertainty is then:

$$0.1\%/\sqrt{3} = 0.0577\%$$

The degrees of freedom would be reasonably high due to the fact that the temperature coefficient was once measured and it is not expected to change significantly over time. The assigned degrees of freedom is therefore 8.

D.7.2.8 Uncertainty of test voltmeter readings due to ambient temperature uncertainty

The temperature stability of the test voltmeter is stated as ± 0.1% / °C within the temperature range of 5 °C to 35 °C in the manufacturer's specification. Since the measured C_t is to be stated as the correction measured at 23 °C, the 0.5 °C standard uncertainty of the measured ambient temperature would contribute to the uncertainty of the measured C_t value. Estimation of the temperature stability could have been carried out by performing a calibration at a different temperature. However, previous calibrations of the voltmeter at different temperatures show that the temperature stability value in the specification is sufficiently accurate for estimating this uncertainty contribution. Additional measurements for a component of such insignificant magnitude would not be warranted in terms of cost. Instead, this contribution is estimated from the manufacturer's specification and past calibrations. The expanded uncertainty of the measured temperature is first approximated by multiplying by its standard uncertainty 0.5 °C with an assumed coverage factor of 2, which gives 1.0 °C. Then according to the manufacturer's specification, this gives a Type B semi-range uncertainty of the test voltmeter reading of 0.1%, which yields a standard uncertainty for a rectangular distribution of:

$$0.1\%/\sqrt{3} = 0.0577\%$$

which is expressed as a percentage of the test voltmeter reading. According to Equation (D.15), the sensitivity coefficient would be approximately −1.

Since the information of the temperature stability is only based on unverified manufacturer's specifications and past calibrations at temperatures outside the range covered by the temperature uncertainty interval of this test, the reliability of this standard uncertainty would be quite low. Therefore, a low of degrees of freedom of 3 is assigned to this component (see D.5).

D.7.2.9 Resolutions of the voltmeters

The resolution of both voltmeters' digital displays is 0.01 kV. At 190 kV, this results in a relative resolution of:

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$100 \times (0.01/190) = 0.0053\ \%$

The semi-range uncertainty of a rectangularly distributed uncertainty component would be equal to half of the resolution, giving a corresponding standard uncertainty of:

$(0.0053/2)/\sqrt{3} = 0.0015\ \%$

Since the limits of the resolution are clearly defined for the uniformly distributed readings within the limits, the degrees of freedom would be quite high. A value of degrees of freedom of 50 may normally be assigned for uncertainty contribution from resolution of digital displays.

A higher value would not make any practical difference and may not be strictly warranted if issues such as filtering and rounding of the displayed values are to be considered.

From Equation (D.14) and Equation (D.15), the sensitivity coefficients would again be 1 and –1 for the reference voltmeter and the test voltmeter respectively.

D.7.2.10 Combined standard uncertainty

The standard uncertainty values described above are listed in Table D.6, together with corresponding degrees of freedom and sensitivity coefficients. The combined standard uncertainty and its effective degrees of freedom, calculated according to Equation (D.3) and Equation (D.5), are also given in the table.

Table D.6—Standard uncertainty values

Component	Standard uncertainty $u(x_i)$ (%)	Degrees of freedom v_i	Sensitivity coefficients c_i	$\lvert c_i u(x_i) \rvert$ (%)
Calibration at 190 kV	0.018	5	1	0.018
Test voltmeter voltage non-linearity	0.2425	5	1	0.2425
Test voltmeter proximity effect	0.1155	5	1	0.1155
Reference voltmeter uncertainty	0.119	18	1	0.119
Deviation of reference voltmeter due to temperature	0.0577	8	1	0.0577
Effect of temperature uncertainty on test voltmeter	0.0577	3	−1	0.0577
Resolution of reference voltmeter	0.0015	50	1	0.0015
Resolution of test voltmeter	0.0015	50	− 1	0.0015
	Effective degrees of freedom, v_{eff}	**11.7**	**Combined standard uncertainty $u_c(y)$ (%)**	**0.3054**

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D.7.2.11 Expanded uncertainty and coverage factor

To obtain the expanded uncertainty, the coverage factor for a level of confidence of 95% needs to be determined. The coverage factor k calculated using Equation (D.8) (or taken from Table D.1) is:

$k = 2.18$

The expanded uncertainty U calculated according to Equation (D.4) is then:

$U = k \times u_c(y) = 2.18 \times 0.3054 = 0.67\,\%$

After rounding, $C_t = -0.1\%$, $U = 0.7\%$ and $k = 2.2$.

The following statement may then be used to report the calibrated correction and its associated uncertainty:

The correction of the voltmeter under test expressed as a percentage of its reading, at an ambient temperature of 23 °C, with no objects placed at a distance less than 0.7 m from the voltmeter, is –0.1 %.

The expanded uncertainty of the correction, also expressed as a percentage of the voltmeter reading, calculated at the level of confidence of 95% is 0.7% with a coverage factor of 2.2.

To assist the user to in using the calibration report, the following note may also be added:

Note: To obtain the corrected value from the voltmeter reading, the following formula may be used:

$$V_{tc} = V_t\left(1 + \frac{C_t(\%)}{100}\right)$$

where

V_{tc} is the corrected voltmeter reading

V_t is the indicated voltmeter reading

$C_t(\%)$ is the percentage voltmeter reading correction reported in this report.

For example, if the indicated voltmeter reading is 100 kV, the corrected voltmeter reading by applying the reported correction of –0.1% will be:

$V_{tc} = 100 \times [1 + (-0.1/100)] = 99.9\ \text{kV}$

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Annex E

(informative)

Partial discharge and corona measurements

E.1 Terms used to characterize partial discharge and corona measurements

The terms “partial discharge” and “corona” are often used interchangeably to describe physical phenomena that differ in a number of respects [B122]. The two terms and the detection equipment used are described herein.

E.1.1 Partial discharges

Partial discharge (PD) is an electric discharge that only partially bridges the insulation between conductors, and may or may not occur adjacent to the conductor. Partial discharges occur when the local electric field strength exceeds the dielectric strength of the insulating medium, resulting in local ionization and breakdown. Depending on the electric field strength, partial discharges are often accompanied by emission of light, heat, sound, and electrical noise in a wide range of frequencies. Partial discharges may be characterized as transient events or as continuous phenomena. Partial discharge electrical noise may be found over a bandwidth from several tens of kilohertz into the gigahertz range depending on the type of insulation structure. In general, the energy content of partial discharge pulses decreases with frequency.

E.1.2 Corona discharges

Corona is a luminous discharge due to ionization of the air (gas) surrounding an electrode caused by a voltage gradient (electric field strength) exceeding a certain critical value. Under certain conditions, corona can be stable due to the high internal resistance of the discharge. Positive and negative coronas can have widely different stability properties. (Positive corona implies that the highly stressed electrode is positive, and the opposite is true for negative corona.)

Under ac conditions, both positive and negative corona discharges will occur around the peaks of the positive and negative voltage half cycles, as opposed to partial discharges, which typically appear on the ascending and descending portions of the ac wave. Corona discharges can assume different forms, exhibiting varied behavior [B156]. Negative glow corona can be stable and continuous, whereas positive glow corona may be continuous, oscillating, fluctuating, or intermittent. Intermittent or pulsed corona includes bursts of low-level current pulses. Some of these types of corona can develop into Trichel streamers (Trichel pulses) or spark discharge under the proper conditions [B122].

E.2 Parameters affecting the magnitude and intensity of partial discharge and corona

E.2.1 Material and geometry of the electrode/insulation structure

Partial discharge and corona generally originate from metallic electrodes that have a high electric field strength at the interface between the electrode and insulating materials. Examples of geometries are: point facing another point, point facing a plane, coaxial conductor inside a tube, parallel straight wires, straight wire facing a plane, hemisphere facing another hemisphere, hemisphere facing a plane, etc.

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E.2.2 Applied voltage

The electric field is directly related to the applied voltage and field intensification, and therefore it affects the magnitude and intensity of corona and partial discharges.

E.2.3 Properties of the ambient gas

Influencing factors include: the pressure, the temperature, and the attaching or non-attaching molecular structure of the gaseous medium.

E.3 Effects of partial discharge and corona on high-voltage equipment

a) Corona that does not lead to sparkover can still cause corrosion or erosion of conductors and insulators. Such corrosion or erosion can occur due to various mechanisms: for example, chain scission of polymer insulation from charged particle impact; decomposition by-products from ambient gas and/or surface contamination chemically reacting to erode surfaces. In a low-pressure environment, ions produced by a positive corona can bombard a surface and cause sputtering, which frees atoms that then can deposit on other surfaces. Therefore, insulators can accumulate a conducting surface by this process. Similarly, partial discharge can cause localized degradation of insulation that can lead to treeing or tracking, causing eventual dielectric failure.

b) Corona and partial discharge currents dissipate energy, which can cause heating of equipment or even alter the operational characteristics of the equipment due to the excess current. A thermal effect of corona can simply be heating of the conductor or insulator surface.

c) Intermittent corona or partial discharge can produce electrical transients in high-voltage circuits and influence control components. A related problem is electrical transients radiated from equipment, causing electromagnetic interference (EMI) problems in other equipment.

E.4 Partial discharge and corona detection methods

E.4.1 Partial discharge pulse detection

Commercially available conventional PD detectors for routine use on cables, capacitors, and transformers are of the wide band type and are designed to operate within the band of about 30 kHz to 800 kHz [B3] [B5] [B26] [B33] [B60] [B126] [B229]. They are charge integrating devices and may be calibrated directly to provide the charge transfers associated with detected discharge pulses in accordance with ASTM method D1868 [B28] and IEC Standard 60270 (listed in Clause 2). Higher bandwidths are utilized in research related work, where faithful reproduction of the PD pulse shapes is of paramount importance. Also for improved pulse resolution, wider bandwidths are employed on work invoking discharge site locations in cables (about 20 MHz), rotating machines (800 kHz to 1 GHz) [B125] [B218] and bus ducts as well as compressed gas cables (about 1 GHz) [B140].

It should be noted that the response of conventional (low bandwidth, resonant-circuit-type) PD pulse detectors falls off as the rise time of the detected PD pulse becomes longer. The rise time of the incident PD

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pulse front at the PD detector input is determined by the initial PD pulse front rise time at the discharge site and any subsequent degradation of the PD pulse rise time along its transmission path from its site of origin to the PD detector end. The latter effect is of particular importance in specimens that exhibit transmission line behavior (e.g., cables, transformers, and rotating machines). However, there are also some important variations within the spark discharge mechanism that may significantly affect the rise time of the discharge pulse formed at the site of its origin as the cavity undergoes successive discharges. For example, this should be considered for atmospheric pressure pseudo glow discharges with long rise times as well as the pulses associated with low-pressure glow discharges [B31].

For subsequent evaluation of PD pulse data, computer based systems or multichannel analyzer systems can be used for PD pulse-height and pulse phase distribution analysis with ac test voltages. The ability to record (for later analysis) the aperiodic PD pulses generated during testing with dc voltage makes this type of instrumentation essential.

E.4.2 Corona discharge detection

Early investigations on corona discharges did not always provide detailed description of either the external detection circuit, the internal impedance of the source, or the electrode assembly [B170], which, along with the properties of the gas, determines the corona discharge behavior. Corona discharges can usually be detected, using conventional PD detectors, though bridge-type, charge integrating detectors are more suitable [B25]. However, corona from overhead power lines is generally measured by employing radio noise meters (tuned frequency spectrum analyzers) with suitable directional antennas. The recorded corona is relatively intense over the AM band (0.55 MHz to 1.60 MHz) but diminishes rapidly thereafter with increasing frequency. Corona may also be characterized by image enhancement devices, which directly observe the phenomena.

E.5 Test procedures

Industry standard PD test specifications on newly manufactured cables, capacitors, transformers, motors, generators, and other apparatus provide partial discharge acceptance values, measured in picocoulombs, which are intended to relate to the quality of the insulation system in the device being tested. It is recognized that these values are somewhat arbitrary in that an accurate correlation between PD activity levels and life expectancy does not exist for most devices.

The primary concern in PD measurements on industrial apparatus is that of sensitivity. High sensitivity levels are particularly difficult to achieve with high capacitance specimens. Balanced-type or bridge circuit PD measurements are used to improve the signal-to-noise ratio. In pressurized gas cables, which behave essentially as low loss transmission lines or waveguides, wide band PD measurements techniques are preferred and high signal-to-noise ratios are achievable. Discharge site location in solid-dielectric extruded cables is normally accomplished using medium bandwidth pulse reflectometry. Installed cables that are readily accessible can be monitored using capacitively coupled or inductively coupled radio frequency probes directly on the cable or cable splice [B32].

Power factor correction capacitors and transformers may employ acoustical PD measurement techniques to locate discharge sites [B97]. In some cases, both electrical and acoustical procedures are employed jointly to characterize magnitude and location simultaneously. Site identification can be improved by the deployment of PD pattern recognition techniques, based either on PD pulse-height/discharge-phase distributions or PD pulse form analysis [B31] [B33] [B88].

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E.5.1 Shielded power cables

PD tests on newly manufactured polymeric cables are essentially go or no-go type tests in that the cable specimens are rejected if they exhibit the presence of discharges at the prescribed sensitivity and voltage test level, or are accepted in their absence [B3] [B4] [B5] [B67].

E.5.1.1 Acoustical method for gas insulated equipment

While acoustical methods are relatively ineffective for PD tests on polymeric and oil/paper-impregnated cables, they are ideally suited for PD site location on compressed gas cables and bus lines. This can be readily accomplished using conventional commercially available ultrasonic detection circuitry depicted in Figure E.1 [B176].Acoustical methods may achieve sensitivity levels of 10 pC to 25 pC [B97]. They are substantially less sensitive than those of electrical PD detectors, which fall in the range between 0.1 pC to 1.0 pC. While acoustical methods can readily detect discharges due to the movement of free conducting particles and those initiated at rough or sharp points on the surface of the cable conductors, they are quite ineffective in detecting the low level PD pulses within hidden cavities inside the spacer insulators [B97].

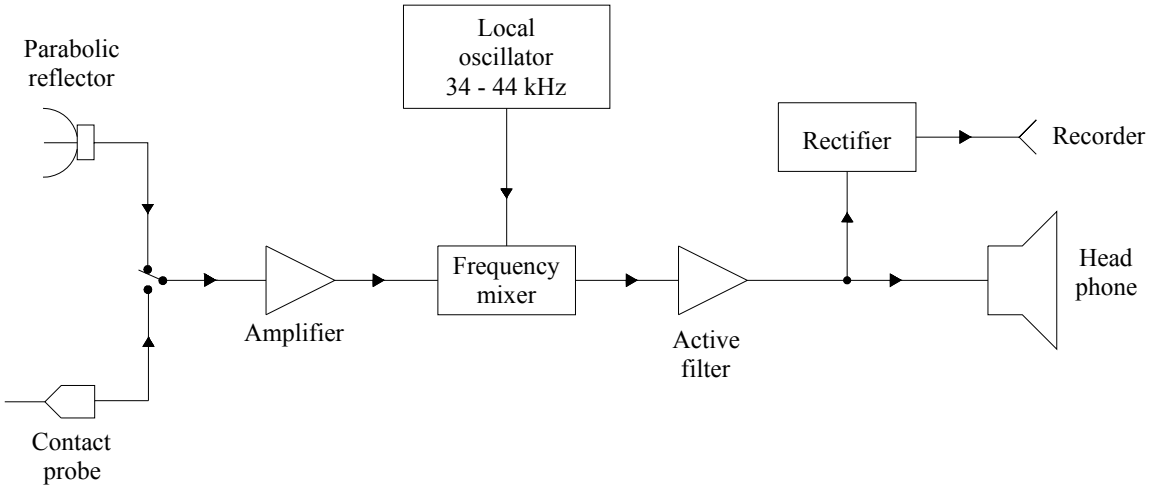


Figure E.1—Schematic circuit diagram of a commercial ultrasonic PD detector [B211]

E.5.2 High-voltage capacitors

Capacitors behave as lumped circuit elements; thus, PD tests on capacitors constitute a simple procedure with the provision that their capacitance should not be too large. Unfortunately, this is not the situation with the vast majority of high-voltage power and energy storage capacitors. If C_p represents the major portion of the capacitance of the capacitor, which shunts the series combination of the capacitance of a discharging cavity in series with an extremely small portion of the dielectric, then in terms of the detected peak discharge pulse voltage signal V_d, the associated apparent charge transfer is given by:

$$\Delta Q = \Delta V_d C_p \tag{E.1}$$

The detected pulse voltage magnitude decreases inversely with the specimen capacitance C_p, eventually approaching a situation where direct electrical PD detection becomes increasingly more difficult when the specimen capacitances begin to exceed 5 μF. Extraneous noise elimination with the reduction in PD tests on high capacitance specimens, using balanced measurement techniques, represents one effective practical means of partially compensating for this reduced measurement sensitivity [B33].

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E.5.2.1 Acoustical methods for high-voltage capacitors

Ultrasound methods are capable of detecting discharges in capacitors having capacitances as high as 40 μF [B97]. Ultrasonic transducers are commonly used for the characterization of PD signals as well as discharge site location.

E.5.3 Transformers and reactors

High-voltage transformers can be represented as complex impedances. As the electrical PD measurements are carried out at the terminals of the transformer, any discharge site within the windings of the transformer is separated from the terminals by a sizable inductance, which appears in parallel with a distributed capacitance and is also shunted to ground by another distributed capacitance. The PD pulse emerging at the discharge site must travel over a complex LC network prior to reaching the terminal of the transformer. As the PD pulse propagates along the transformer winding, it is both attenuated and distorted as its high frequency content is removed or filtered out. In addition, the occurrence of resonances, between windings and turns within the windings, can introduce errors into the measured PD quantities should these resonant frequencies fall within the bandwidth of the PD sensing system.

E.5.3.1 Partial discharge tests on transformers and reactors

Partial discharge tests on the transformers may be performed using either the so-called induced test or by means of a separate independent power frequency voltage source to produce the voltage stress in the insulating system [B60]. In the induced test, the voltage is applied across the low potential winding whereby the voltage stress is impressed between the individual turns and sections of the windings as under normal operating conditions in service. When this test is employed with larger transformers, it is common practice to use the third or higher harmonic of the power frequency source in order to permit an overvoltage test on the transformer without saturating the magnetic core and thereby causing damage to the transformer. Since high power transformers are normally equipped with a capacitive bushing tap [B48] [B60] [B126] [B180] [B231], partial discharge measurement circuits may be connected directly to this tap. Figure E.2 shows the connection diagram for an induced voltage PD test on a power transformer specimen [B31].

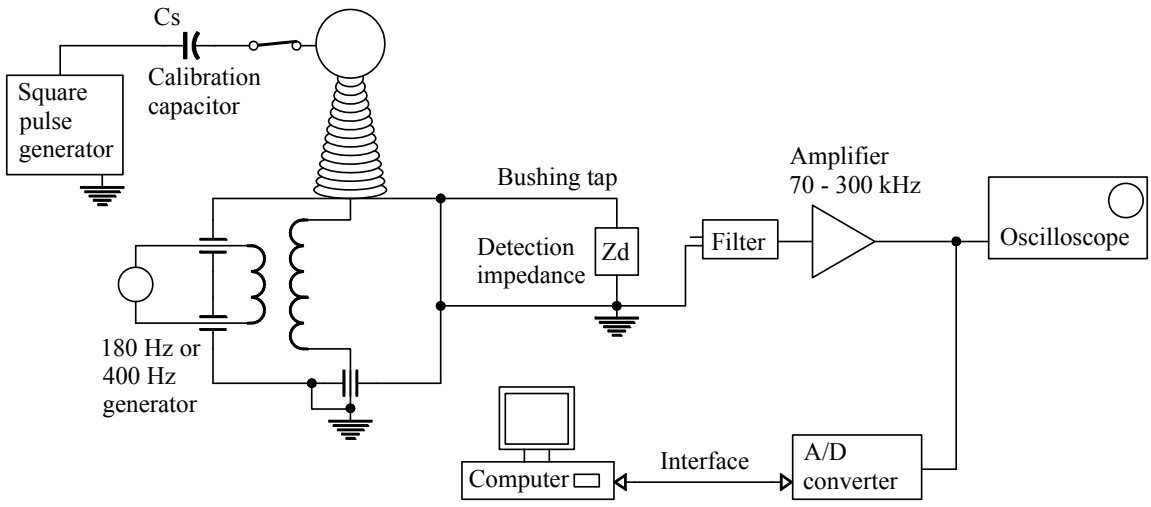


Figure E.2—Schematic circuit arrangement of an induced voltage PD test on a power transformer, including a measurement system for PD pulse-height distribution analysis [B31]

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For smaller transformers, the power frequency voltage is generally applied to the high-voltage winding by means of a discharge-free test transformer as shown in Figure E.3 [B31]. The transformer insulation is thus electrically stressed between the high-voltage winding and the low-voltage winding as well as ground. Note that with this arrangement a discharge-free coupling capacitor C_c is required.

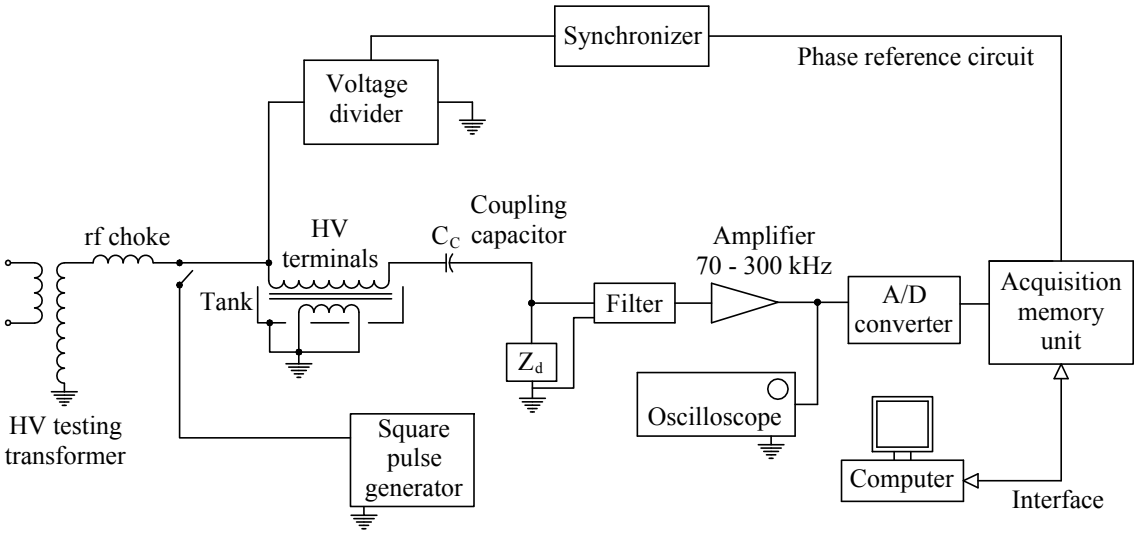


Figure E.3—Schematic circuit diagram for a partial discharge test on a small transformer, using a separate 60 Hz high-voltage discharge-free test source with additional instruments for PD pulse-height and discharge phase distribution measurements [B31]

E.5.3.1.1 Test bandwidth specifications

While PD specifications state a permissible bandwidth ≤ 300 kHz in the testing of transformers [B126], a lower flat bandwidth extending from 40 kHz to 200 kHz has been found to provide improved sensitivity [B229].

E.5.3.1.2 Partial discharge measurement analysis

Computer based systems or multichannel analyzer systems can be used for PD pulse-height and pulse phase distribution analysis. Partial discharge measurement standards on transformers require only the determination of the PD inception and extinction voltages as well as the maximum PD charge transfer value and its change with time at specified voltage levels.

E.5.3.1.3 Radio influence voltage (RIV) test method

Some transformer customers may require that a radio influence voltage (RIV) test be performed. This test uses a resonant circuit for PD detection in transformers, which forms the basis for apparent charge measurements quantified in microvolts and not picocoulombs. The RIV reading in microvolts is a complex function of the PD pulse magnitude and repetition rate and, as a consequence, does not bear a relationship to the measured PD pulse value in picocoulombs [B98].

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E.5.4 Rotating machines

Rotating machine insulation commonly operates in the presence of PD discharges, whose intensity under certain conditions may attain substantially elevated levels. As a consequence, the approach to PD measurement on rotating machines differs appreciably from that on other electrical apparatus and cables in that it is essentially designed and implemented to monitor the discharge activity. The most effective approach appears to center on the accumulation and subsequent analysis of field PD data obtained over regular test intervals on the same machine as well as on other machines of similar design, a task in which the expert observer plays a critical role.

E.5.4.1 Rotating machine partial discharge detection methods

There are a number of PD detection methods that can be used on rotating machines. A compendium of some of these methods is given in [B124].

E.5.4.1.1 Early detection methods used

An early method for PD detection in rotating machines was done by Johnson and Warren [B132], who detected the PD pulses across the neutral resistor of a generator while in operation as shown in Figure E.4.

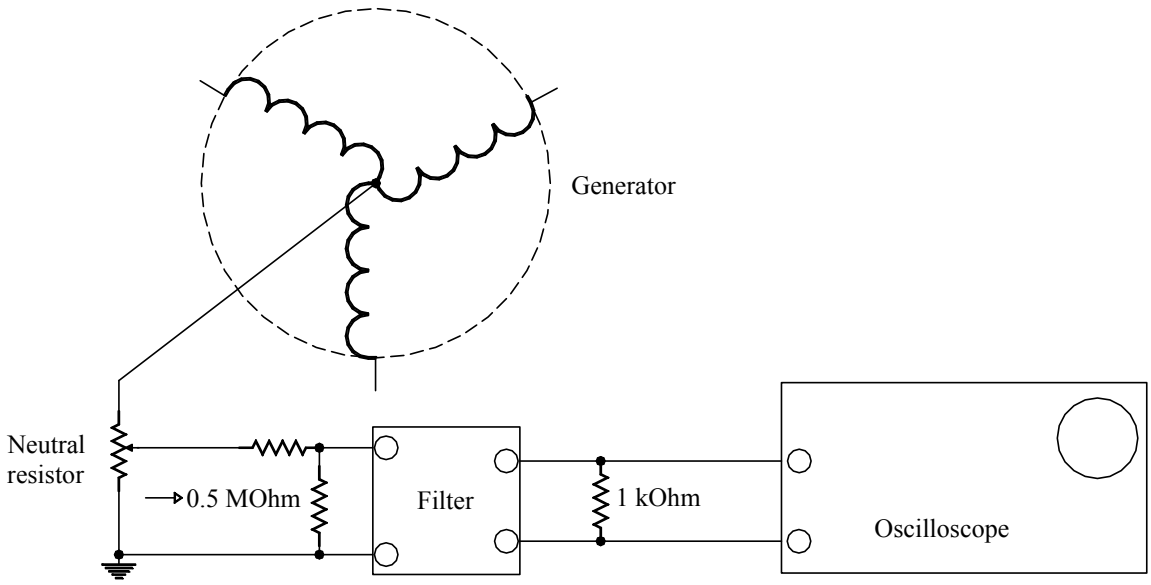


Figure E.4—Early PD detection system for on-line tests on a generator (after Johnson and Warren [B132]

Kurtz [B144] modified the off-line test procedure described by Johnson [B131]. In order to further improve the signal-to-noise ratio, a series of changes were introduced into the measurement circuitry first by Kurtz et al. [B145] [B146] and subsequently by Stone et al. [B103] [B155] [B157] [B219] [B220], who utilized delay lines in conjunction with a balanced PD measurement scheme as portrayed in Figure E.5.

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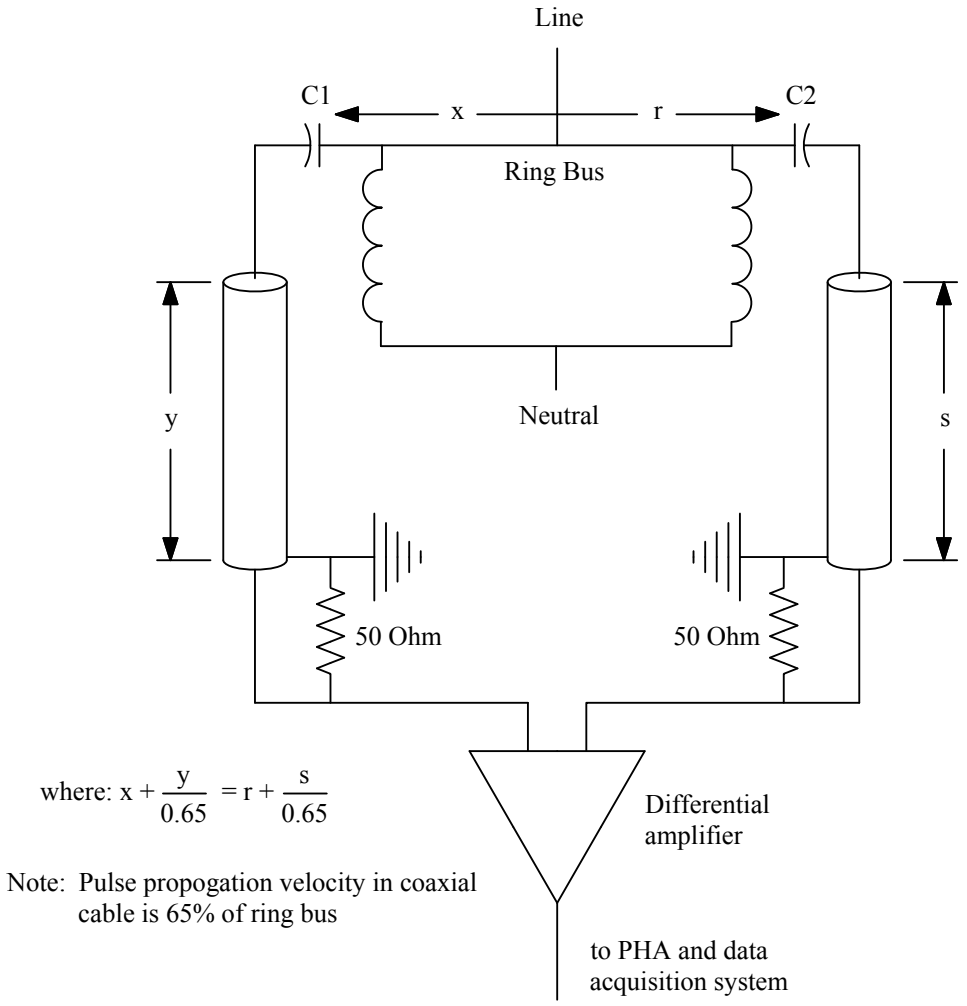


Figure E.5—Balanced permanent coupler connections for a water-wheel generator (after Bromley and McDermid [B47]

E.5.4.1.2 PD detection on rotating machines using capacitive couplers

Partial discharge detection on rotating machines is also performed with capacitive couplers connected directly to the terminals of the machine. Bandwidths used generally range from 300 kHz up to 20 MHz and the measurement systems are calibrated in picocoulombs. The preferred couplers are capacitive, but occasionally Rogowski coils are employed.

E.5.4.2 Use of wide band and narrow band PD detectors

When PD measurements are carried out using wide band and narrow band PD detectors on rotating machines, the measured PD signal response will not only depend upon the bandwidth of the detector but also on the type of machine specimen under test. Partial discharge signal propagation in machines is almost as complex as in transformers, the latter specimens having the additional complication of pronounced resonance effects, not only between phase coils but also between the numerous turns within each coil.

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E.5.4.3 Off-line tests on rotating machines

Off-line tests on rotating machines are normally carried out during general maintenance periods over which it is possible to examine machine windings for possible discharge induced degradation and determine whether replacement of any aged bars is warranted. The high-voltage stators of the machines may be tested with the rotors installed or removed; usually portable 50/60 Hz power supplies are employed for this purpose, although tests may also be performed at 0.1 Hz [B43] [B153]. Off-line PD tests are commonly carried out with conventional 300 kHz wide band detectors, calibrated in apparent charge units in accordance with ASTM Method D1868 [B27] and IEC Standard 60270 (listed in Clause 2).

E.5.5 Low pressure environments

Many aerospace flight vehicles, such as advanced aircraft and reusable launch-to-orbit systems, experience a wide range of operating pressures during their flight profiles. High-voltage components onboard such vehicles will periodically experience PD with exposure duration depending on flight altitudes. Critical components can require off-line PD qualification testing in an altitude-simulating environment. Characterizations of the waveforms of partial discharge current pulses were accomplished in the pressure range of 13.3 Pa to 101.3 kPa (0.1 Torr to 760 Torr) in air, argon, and helium [B135]. This corresponds to an altitude range of sea level to about 60 000 meters (200 000 feet). Difficulties in adhering to measurement guidelines defined by the IEC Standard 60270 (listed in Clause 2) are described, and suggested modifications of the standard procedures are presented for measurements and calibration for low-pressure PD [B87]. This is primarily relevant to PD measurements at pressures corresponding to altitudes above about 12 000 meters (40 000 feet).

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Annex F

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