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(Revision of
IEEE Std 4-1978)

IEEE Standard Techniques for High-Voltage Testing

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IEEE Standard Techniques for High-Voltage Testing

Sponsor

Power Systems Instrumentation and Measurements Committee of the IEEE Power Engineering Society

Approved March 16, 1995

IEEE Standards Board

Abstract: This standard establishes standard methods to measure high-voltage and basic testing techniques, so far as they are generally applicable, to all types of apparatus for alternating voltages, direct voltages, lightning impulse voltags, switching impulse voltages, and impulse currents. This revision implements many new procedures to improve accuracy, provide greater flexibility, and address practical problems associated with high-voltage measurements.
Keywords: high-voltage testing, testing

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Foreword

(This foreword is not a part of IEEE Std 4-1995, IEEE Standard Techniques for High-Voltage Testing.)

This revision of *IEEE Standard Techniques for High-Voltage Testing* is notable for its implementation of many new procedures to improve accuracy, provide greater flexibility, and address practical problems associated with high-voltage measurements. Users of this document are urged to study it carefully to learn about the differences between it and previous versions. A significant effort has been made to clarify some of the techniques that may have been difficult to interpret, eliminate methods that are not technically sound, and provide the user with sufficient guidance.

Introduction

(This introduction is not a part of IEEE Std 4-1995, IEEE Standard Techniques for High-Voltage Testing.)

The current revision of this standard is the seventh 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 Institute's standards into separate sections, 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 of measurement of high voltage and basic testing techniques, so far as they are generally 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 in preparing this document:

IEEE Std 1122-1987, IEEE Standard for Digital Recorders for Measurement in High-Voltage Impulse Tests (ANSI).

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

IEC Publication 60-1 (1989), High-voltage test techniques—Part 1: General definitions and test requirements.

IEC Publication 507 (1991), Artificial pollution tests on high-voltage insulators to be used on a.c. systems.

IEC Publication 1245 (1993), Artificial pollution tests on high-voltage insulators to be used on d.c. systems.

Major revisions contained in this document are the description of the wet test procedure, methods for artificial contamination tests, and techniques for ensuring accuracy in high-voltage measurements. Especially significant for impulse measurements is the inclusion of a comparison method in which tests may be performed at relatively low voltage with a reference divider.

At the time this standard was completed by the High-Voltage Testing Techniques Subcommittee of the Power Systems Instrumentation and Measurements Committee, the following members contributed actively to its revision:

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Contents

IEEE Standard Techniques for High-Voltage Testing

1. Overview

1.1 Scope

This standard is applicable to

a) Dielectric tests with direct voltages
b) Dielectric tests with alternating voltages
c) Dielectric tests with impulse voltages
d) Tests with impulse currents
e) Tests with combinations of the above
f) 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.

1.2 Purpose

The purpose of this standard is to

a) Define terms of general applicability
b) Present general requirements regarding test equipment, objects, and procedures
c) 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 appropriate apparatus committee standards.

2. References

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

ANSI C39.1-1981 (Reaff. 1992), American National Standard Requirements for Electrical Analog Indicating Instruments.[1]

IEEE Std 1122-1987, IEEE Standard for Digital Recorders for Measurement in High-Voltage Impulse Tests (ANSI).[2]

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

3. Definitions

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

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

3.3 chopped lightning impulse: A prospective full lightning impulse during which any type of discharge causes a rapid collapse of the voltage.

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

3.5 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.

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

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

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

3.9 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.

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

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

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

3.11 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.

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

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

3.14 full lightning impulse: A lightning impulse not interrupted by any type of discharge.

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

3.16 instant of chopping: The instant when the initial discontinuity appears.

3.17 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.

3.18 lightning impulse: An impulse with front duration up to a few tens of microseconds.

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

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

3.21 nonsustained disruptive discharge: A momentary disruptive discharge.

3.22 overshoot: The value by which a lightning impulse exceeds the defined crest value.

3.23 partial discharge: A discharge that does not completely bridge the insulation between electrodes. *See*: IEEE Std C57.113-1991.[3]

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

3.25 peak value of impulse voltages: The maximum value of impulses that are smooth double exponential waves without overshoot.

3.26 *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.

3.27 precision: The discrepancy among individual measurements.

3.28 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.

3.29 puncture: A disruptive discharge through solid insulation.

3.30 random error: Errors that have unknown magnitudes and directions and that vary with each measurement.

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[3]Information on references can be found in clause 2.

3.31 response (*G*): The output, as a function of time or frequency, when a step input voltage or current is applied to the system.

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

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

3.34 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.

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

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

3.37 standard chopped lightning impulse: A standard lightning impulse chopped by an external gap after 2–5 μs.

3.38 standard lightning impulse: A full lightning impulse having a virtual front time of 1.2 μs and a virtual time to half-value of 50 μs.

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

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

3.41 switching impulse: An impulse with a front duration of some tens to thousands of microseconds.

3.42 systematic error: Errors where the magnitudes and directions are constant throughout the calibration process.

3.43 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.

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

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

3.46 value of the test voltage for alternating voltage: The peak value divided by the square root of 2, or the rms value as defined by the appropriate apparatus standard.

3.47 value of the test voltage for lightning impulse voltage: The peak value when the impulse is without overshoot or oscillations. See clause 7 for further explanation.

3.48 virtual front time of a lightning impulse (T_1): The time interval between the instants when a smooth impulse is 30% and 90% of the peak value multiplied by 1.67. See clause 7 for further explanation.

3.49 virtual origin (O_1): The intersection with the time axis of a straight line drawn as a tangent to the steepest portion of the impulse or response curve. See 7.1.4 and 13.4.6.1 for further explanation.

3.50 virtual time to half-value (T_2): The time interval between the virtual origin and the instant on the tail when the voltage has decreased to half of the peak value.

3.51 voltage at the instant of chopping: The voltage at the instant of the initial discontinuity.

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

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

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

4. General requirements

4.1 Arrangement of the test object

4.1.1 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 flashover voltage. For this reason, the general arrangement should be specified by the appropriate apparatus standard.

4.1.2 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 values of clearances may be obtained from the relationship between the critical flashover voltage of rod to plane gaps:

$$V_{50} = \frac{3400}{\left(1 + \frac{8}{d}\right)} \qquad (1)$$

where

V_{50} is the critical flashover 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

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

where

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

Equations (1) and (2) may then be used to determine the appropriate gap spacing to withstand a given voltage level. Alternatively, the curves given in figure 1 may be used.

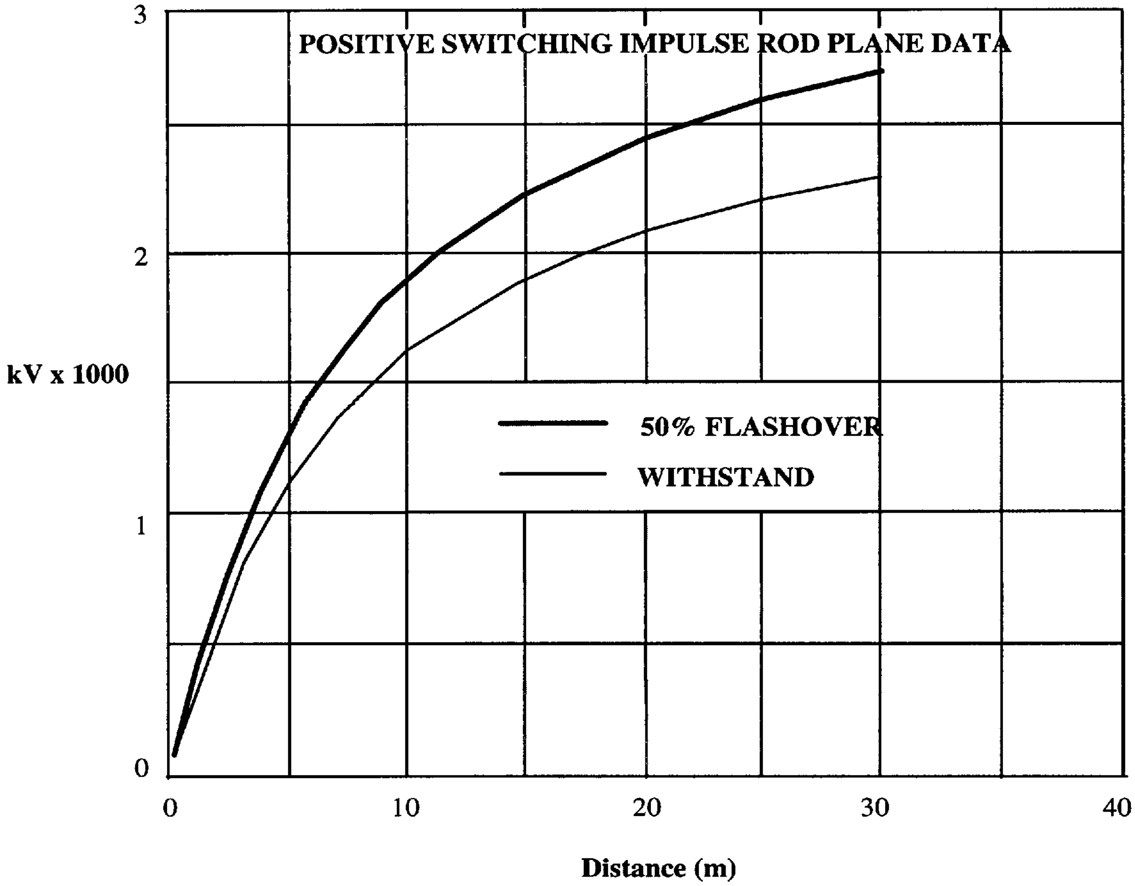


Figure 1—Voltage versus distance for rod-plane gap

4.2 Interpretation of discharges in high-voltage tests

4.2.1 Disruptive discharges

A disruptive discharge is a discharge that completely bridges the insulation under test, reducing the voltage between the electrodes practically to zero. Disruptive discharges are subject to random variation and, usually, a number of observations have to be made in order to obtain a statistically significant value of the disruptive discharge voltage. The test procedures described in this standard are based on statistical considerations. Statistical methods for the evaluation of test results obtained from these procedures are provided.

It should be recognized that the occurrence of a disruptive discharge in self-restoring insulation may affect the probability of occurrence of subsequent disruptive discharges. The discharge statistics that are used to determine the probability parameters of the breakdown voltage require the probability distribution to be unchanged during the tests carried out according to statistical procedures. The occurrence of a disruptive discharge may degrade the insulation and change the initiation site to some degree. Such changes may make it difficult to interpret the test results on a statistical basis.

If the probability distribution of the disruptive discharge voltage is close to a normal distribution, the conventional deviation of the disruptive discharge voltage (z) is correspondingly close to its standard deviation.

4.2.2 Nonsustained disruptive discharges

Nonsustained disruptive discharges are discharges in which the test object is momentarily bridged by a spark or arc. During these events, the voltage across the test object is momentarily reduced to zero or to a very small value. Depending on the characteristics of the test circuit and the test object, a recovery of dielectric strength may occur and may even permit the test voltage to reach a higher value. Such an event shall be interpreted as a disruptive discharge unless otherwise specified by the appropriate apparatus standard.

4.2.3 Nondisruptive discharges

Nondisruptive discharges, such as those between intermediate electrodes or conductors, may also occur without reduction of the test voltage to zero. These shall be interpreted as nondisruptive discharges unless otherwise specified by the appropriate apparatus standard.

5. Tests with direct voltage

5.1 Test voltage

5.1.1 Requirements for the test voltage

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

5.1.2 Generation of the test voltage

The test voltage is generally obtained by means of rectifiers, although electrostatic generators may be employed. The requirements to be met by the test voltage source depend considerably upon the type of apparatus that is to be tested and on the test conditions. These requirements are determined mainly by the values and nature of the test current to be supplied, the important constituents of which are indicated in 5.1.4.

The output current rating of the voltage source should be sufficient to charge the capacitance of the test object in a reasonably short time (see 5.2.1). In the case of objects having high capacitance, charging times of several minutes may be required. The voltage source, including its storage capacitance, should be adequate to supply the leakage and absorption currents, and any internal and external partial discharge currents, with a voltage drop of less than 5%. Special requirements for voltage drop in the case of pollution tests are given in clause 15. In tests on internal insulation, these currents are usually small, but when testing wet insulators, leakage current on the order of several milliamperes, or partial discharge pulses on the order of 0.01 C, may occasionally be encountered.

5.1.3 Measurement of the test voltage

5.1.3.1 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 should, in general, be made with devices that have passed the approval procedures referred to in clause 12. Attention is drawn to the requirements on response characteristics of devices used for measuring ripple factor or transients.

5.1.3.2 Calibration of a nonapproved measuring device with an approved measuring device

The procedure usually consists of establishing a relationship between the output signal of some device related to the test voltage and a measurement of the same voltage performed in accordance with 5.1.3.1 or with another device that meets the requirements of this standard.

This relationship may be dependent on the presence of the test object, the sphere gap or rod gap, the precipitation in wet tests, etc. Hence, it is important that these conditions are the same during the calibration and the actual test, except that during the test the sphere gap or rod gap shall be opened sufficiently to prevent sparkover.

Attention is drawn to the precautions necessary when using a sphere gap under direct voltage, due to the occurrence of flashovers at lower voltage values predominantly resulting from foreign particles.

NOTES

1—The problem of foreign particles can be overcome by providing a clean, particle free, air flow of not less than 3 m/s through the gap.

2—In the presence of ripple voltages, sphere gaps measure the peak of the applied voltage.

The calibration is preferably made at or near 100% of the test voltage, but for tests on nonself-restoring insulation, extrapolation may be made from a value not lower than 20% of this voltage, provided that tests have demonstrated that the measurement circuit is linear up to the test voltage.

5.1.3.3 The rod gap as an approved measuring device

A rod gap with dimensions as given in clause 17, and used in accordance with this clause, is an approved measuring device for direct voltage. These gaps are most accurate when used with voltages above 135 kV and less than 1335 kV.

5.1.4 Systems for measuring the steady-state value of direct voltages

a) *Instrument used with series resistor:* A dc measuring instrument is connected in series with a stable high ohmic value resistor.
b) *Instrument used with voltage divider:* A voltmeter is connected across the low-voltage arm of a resistor voltage divider. The resistance of the voltmeter shall be taken into account when determining the ratio of the divider.

NOTE—Depending on the type of instrument used, these methods will determine the mean, the rms, or the peak value of the voltage.

c) *Electrostatic voltmeter:* An electrostatic voltmeter has two electrodes that are connected to the points between which the high voltage is to be measured. The electrostatic field between the electrodes generates an attracting 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.

d) *Generating voltmeter:* A generating voltmeter is a capacitive device, the input terminals of which are connected to the points between which the voltage is to be measured. It is essentially a variable capacitor, the capacitance being periodically changed between two fixed values. A measuring instrument, together with a suitable switching or rectifying device, measures the change of charge that, in general, is proportional to the mean value of the direct voltage.

5.1.5 Systems for measuring ripple voltage

a) *Oscilloscope used with voltage divider:* An oscilloscope is connected to the low-voltage arm of a voltage divider having a suitable frequency response. It should be noted that the capacitance of the cable between the divider and the instrument can modify the frequency response and that the ripple measuring system itself can modify the ripple content of the system.
b) *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.
c) *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. The average value of the rectified current, I_r, flowing through the capacitor is then related to the ripple amplitude, V_r, by (subject to two requirements)

$$V_r = \frac{I_r}{4Cf} \qquad (3)$$

where

C is the capacitance of the capacitor
f is the frequency of the fundamental

1) There can be only one peak during each half-cycle
2) The positive and negative half-cycles need to have the same peak values

Because the ripple amplitude is defined in terms of half the difference between maximum and minimum values, the second restriction is met by definition. Subject to the same restrictions, the ripple amplitude is related to the average value of the rectified current by the following expression if a half-wave rectifier is used in place of a full-wave rectifier:

$$V_r = \frac{I_r}{2Cf} \qquad (4)$$

5.1.6 Measurement of the test current

When measurements of current through the test object are made, a number of separate 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) The 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

Measurements of the first three 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 sometimes be obtained by observing current variations with respect to time.

The relative magnitude and the importance of each component of current depend on the type and the conditions of the test object, the purpose of the test being made, and the duration of the test. Accordingly, the measurement procedures should be specified by the appropriate apparatus standard, especially when it is required to distinguish a particular component.

Measurements of partial discharge pulse currents in transformers are made with special instruments that are contained in IEEE Std C57.113-1991. Procedures for measuring partial discharges in cables are found in the relevant ICEA and AEIC specifications.

5.2 Test procedures

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 19.

5.2.1 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. The test requirements are generally satisfied if no disruptive discharge occurs on the test object.

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 appropriate apparatus standard.

5.2.2 Disruptive discharge voltage tests

The voltage shall be applied and raised continuously until a disruptive discharge occurs on the test object. The value of the test voltage reached at the instant of the disruptive discharge shall be recorded. The appropriate apparatus standard shall specify the rate of rise of the voltage, the number of voltage applications, and the procedure for evaluation of the test results.

5.2.3 Assured disruptive discharge voltage tests

The voltage shall be applied and raised continuously until a disruptive discharge occurs on the test object. The value of the test voltage reached at the instant of the disruptive discharge shall be recorded.

The appropriate apparatus standard shall specify the voltage rate of rise and 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. Tests with alternating voltage

6.1 Test voltage

6.1.1 Requirements for the test voltage

The test voltage shall be an alternating voltage having a frequency in the range of 45–65 Hz, normally referred to as power-frequency voltage. Special tests may be required at frequencies considerably below or above this range, as specified by the appropriate apparatus standards.

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 the square root of 2 within ±5%.

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

6.1.2 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 be stable enough to be practically unaffected by varying leakage currents. Nondisruptive discharges in the test object should not reduce the test voltage to such an extent, and for such a time, that the measured disruptive discharge voltage of the test object is significantly affected.

Nonsustained disruptive discharges may cause overvoltages on the test object and on the test transformer, if used. This phenomenon is a result of uncontrolled resonance conditions produced by the interaction of leakage inductance of the alternating voltage source and the varying impedance of the high-voltage circuit. This condition may be eliminated by providing sufficient damping resistance in the high-voltage circuit or by short-circuiting the primary voltage to the high-voltage test transformer immediately following a disruptive discharge. Controlled high-voltage resonant circuits do not produce overvoltages following disruptive discharges since they "de-tune" whenever the load impedance changes.

6.1.2.1 Requirements for the transformer test circuit

To assure that the test voltage is practically unaffected by transient leakage currents, the short-circuit current delivered by the transformer should be sufficient to maintain the test voltage within 3% during transient current pulses or discharges.

Guidelines for achieving this requirement are

a) For dry tests on small samples of solid insulation, insulating liquids, or combinations of the two, a short-circuit current on the order of 0.1 A (rms) to 0.5 A is normally sufficient

b) For artificial contamination tests or for tests on external self-restoring insulation (insulators, disconnecting switches, etc.), short-circuit currents above 0.5 A (rms) may be required

NOTES

1—When the test circuit is supplied by a rotating generator, the transient short-circuit current should be used. The capacitance of the test object and any additional capacitance should be sufficient to ensure that the measured disruptive discharge voltage is unaffected by partial discharges in the test object. A capacitance in the range of 0.5–1.0 nF is generally sufficient.

2—If any protective resistor external to the test transformer does not exceed 10 kΩ, the effective terminal capacitance of the transformer may be regarded as being in parallel with the test object.

The voltage stability can be verified by directly recording the voltage applied to the test object by means of a suitable high-voltage measuring system.

An exception to the tests on appliances and small samples of solid insulation, and for tests on insulating liquids (or combinations of the two) is that a short-circuit current of 0.1 A may suffice.

6.1.2.2 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 considerably greater than that of the source and with a substantially sinusoidal shape.

The series resonant circuit is useful when testing objects in which the leakage currents are very small in comparison with the capacitive currents. The circuit may be unsuitable for testing external insulation under contaminated conditions

6.1.2.3 The parallel resonant circuit

The parallel resonant circuit consists essentially of a capacitive test object or load in parallel with a variable inductance and a high-voltage source. By varying the inductance, the circuit can be tuned, resulting in a considerable reduction in the current drawn from the high-voltage source.

6.1.3 Measurement of the test voltage

6.1.3.1 Systems for measuring the amplitude of alternating voltages

The following systems will in most cases 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 item c)] determines the peak-to-peak amplitude, and the electrostatic voltmeter [see item d)] measures the rms value.

Overstressing of components in measuring equipment can occur upon flashover of a test object. Additional measuring errors can be introduced by partial discharges. These phenomena are usually associated with measuring systems with a substantial increase in the frequency response at high frequencies; they are generally caused by residual inductances and stray capacitances.

a) *Instrument used with voltage transformer:* A voltmeter is connected across the low-voltage winding of a voltage transformer of either the inductive or capacitive type. In general, the choice of the instrument is not restricted by its input impedance.
b) *Instrument used with voltage divider:* A voltmeter or an oscilloscope is connected across the low-voltage arm of the divider through a measuring cable. In general, the input impedance of the low-voltage measuring circuit, including the measuring cable, affects the divider ratio. In most cases, a capacitive voltage divider together with a low-voltage circuit measuring the peak value of the high voltage is used.

c) *Capacitor used with a rectifying device:* A capacitor in series with a full-wave rectifier is connected to the points between which the voltage is to be measured. The peak value of the voltage, V_p, is related to the rectified mean current, I_r, flowing through the capacitor by

$$V_p = \frac{I_r}{4Cf} \quad (5)$$

where

C is the capacitance of the capacitor
f is the frequency of the test voltage

If the ammeter measuring the capacitor current is connected so that only alternate half-cycles of current are measured, the factor 4 in the above expression becomes 2. This method is of limited application.

If the waveform has more than one peak during each half-cycle, then the accuracy depends upon the waveform.

d) *Electrostatic voltmeter:* This device is described in item c) of 5.1.4 for use with direct voltages. It can also be used for measuring the rms value of alternating voltages in a large range of frequencies up to several megahertz.

e) *Generating voltmeter:* A generating voltmeter for use with direct voltage is described in item d) of 5.1.4. Such a voltmeter can also be used for the measurement of alternating voltages. By a suitable choice of frequency of the capacitance variation and its phase angle relative to the voltage to be measured, the peak value or any intermediate value can be determined.

f) *Instrument used with series resistor:* An ac measuring instrument is connected in series with a stable high ohmic value resistor.

6.1.3.2 Systems for measuring the amplitude of harmonics

a) *Oscilloscope used with voltage divider:* An oscilloscope is connected across the low-voltage arm of a capacitor voltage divider. This method is sufficient only if the accuracies of both the recording and the subsequent analysis are sufficient to ensure that the requirements are met. The method has limited accuracy, especially in the case of low-amplitude harmonics.

b) *Instrument used with filter:* A filter is used to suppress the fundamental component of the voltage, and the rms value of the residual harmonics is measured with an appropriate instrument. Alternatively, but with less accuracy, the peak value of the combined harmonics may be measured with an appropriate instrument.

c) *Wave analyzer used with voltage divider:* This system permits separate measurement of the rms value of the fundamental and each harmonic.

6.1.3.3 Measurement with approved devices

The measurement of voltages shall be made with devices that have passed the approval procedures referred to in clauses 12, 13, and 17.

6.1.3.4 Calibration of a nonapproved measuring device with an approved measuring device

The procedure usually consists of establishing a relationship between the output signal of some device related to the test voltage and a measurement of the same voltage performed in accordance with a sphere gap used in accordance with clause 17. This relationship may be dependent on the presence of the test object, the sphere gap, the precipitation in wet tests, etc. Hence, it is imperative that these conditions are the same during the calibration and the actual tests, except that during the test the sphere gap shall be opened sufficiently to prevent sparkover.

The calibration is preferably made at three levels (approximately 50%, 65%, and 80%) of the test voltage. These three voltage levels shall agree with table 11. For tests on objects with nonself-restoring insulation, extrapolation may be made from a value not lower than 20% of the test voltage if linearity is proven. Extrapolation may be unsatisfactory if the current in the test circuit varies nonlinearly with the applied voltage or if any changes occur in the voltage shape or frequency between the calibration and the test.

6.2 Test procedures

The disruptive discharge voltage of a test object is subject to statistical variations. Some guidance on methods for determining voltages giving specified disruptive discharge probabilities is given in clause 19.

6.2.1 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% per second of the test voltage. For low-voltage testing (up to 1000 V) the rate of rise can be greater provided that there is no overshoot of the 100% level. 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. The requirements of the test are generally satisfied if no disruptive discharge occurs on the test object.

Deviations from this recommendation may be specified by the appropriate apparatus standard.

6.2.2 Assured disruptive discharge voltage tests

The voltage should be raised in the manner described in 6.2.1 until a disruptive discharge occurs on the test object. The value of the test voltage reached just prior to the disruptive discharge should be recorded. The requirements of the test are generally satisfied if this voltage is not higher than the assured disruptive discharge voltage on each one of a specified number of voltage applications.

6.2.3 Capacitance and dielectric loss measurements

6.2.3.1 General

Insulating materials are generally used either to

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

6.2.3.2 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 2, together with their respective vector 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.

It should be noted that the values of equivalent resistance (*R*) and capacitance (*C*), 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.

6.2.3.3 Evaluation of dielectric loss parameters

Quantities related to dielectric losses are obtained from the following equations for the respective circuits of figure 2 as follows:

a) Parallel equivalent circuit

$$\text{Dissipation factor (or tan } \delta\text{)} = \frac{I_r}{I_c} = \frac{1}{\omega R_p C_p} \tag{6}$$

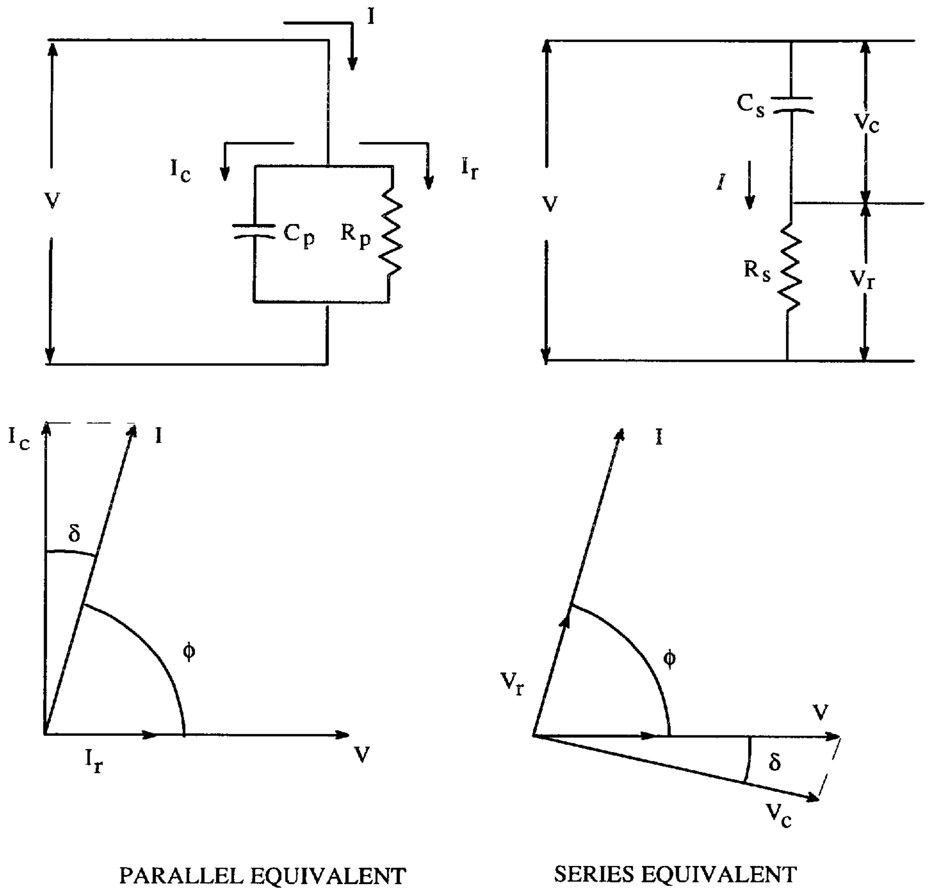
$$\text{Power factor (or cosine } \phi\text{)} = \frac{I_r}{I} = \frac{1}{\sqrt{1+\omega^2 R_p^2 C_p^2}} \tag{7}$$

b) Series equivalent circuit

$$\text{Dissipation factor (or tan } \delta\text{)} = \frac{V_r}{V_c} = \omega R_s C_s \tag{8}$$

$$\text{Power factor (or cosine } \phi\text{)} = \frac{V_r}{V} = \frac{\omega R_s C_s}{\sqrt{1+\omega^2 R_s^2 C_s^2}} \tag{9}$$

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



I_c is the current through the capacitor
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
R_s is the resistance of the series circuit

Figure 2—Equivalent circuits for dielectric loss measurement

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

$$C_p = \frac{C_s}{1 + (\tan\delta)^2} = \frac{C_s}{1 + (\omega R_s C_s)^2} \tag{10}$$

where

$$C_s = C_p\,[1 + (\tan\delta)^2] = C_p\left[1 + \frac{1}{(\omega R_p C_p)^2}\right] \tag{11}$$

$$R_p = R_s\left[1 + \frac{1}{(\tan\delta)^2}\right] = R_s\left[1 + \frac{1}{(\omega R_s C_s)^2}\right] \tag{12}$$

$$R_s = \frac{R_p}{1 + \frac{1}{(\tan\delta)^2}} = \frac{R_p}{1 + (\omega R_p C_p)^2} \qquad (13)$$

6.2.3.4 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. They are described in the following subclauses; however, a large number of generic variations are commercially available, and their corresponding balance equations may be different from those presented here. In this case, the instruction manual of the manufacturer should be consulted. In the following subclauses, the parallel equivalent circuit is assumed.

6.2.3.4.1 Schering bridge

The basic circuit is shown in figure 3. At balance, the values of R_p and C_p are given by

$$R_p = R_3\left(\frac{C_4}{C_s}\right) \qquad C_p = C_s\left(\frac{R_4}{R_3}\right) \qquad (14)$$

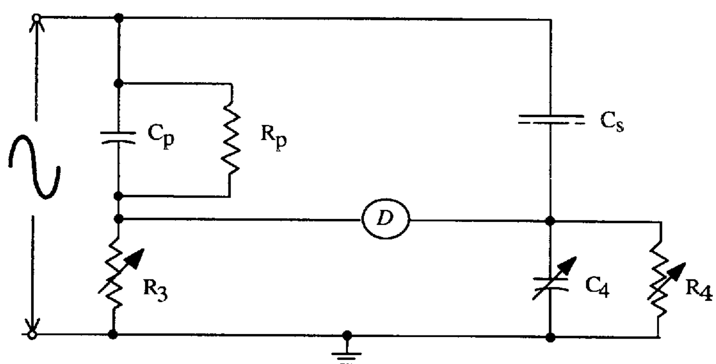
where

R_3, R_4 are variable resistors in the bridge

C_4 is a variable capacitor in the bridge

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

$$\delta = 1/(\omega R_p C_p) \qquad (15)$$



C_s is the reference capacitor

Figure 3—Measurement method—Schering bridge basic circuit

6.2.3.4.2 Transformer ratio-arm bridge

A typical circuit for this type of bridge is shown in figure 4. 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.

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

$$R_p = \frac{N_1}{N_2} \cdot \left(\frac{1}{\omega^2 R_2 C_2 C_s}\right) \tag{16}$$

where

R_2 is a variable resistor in the bridge
C_2 is a capacitor in the bridge

$$C_p = \frac{N_2}{N_1} \cdot \left(\frac{C_s}{1 + \omega^2 R_2^2 C_2^2}\right) \tag{17}$$

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

$$\delta = \frac{1}{\omega R_p C_p} \quad or \quad \delta = \omega R_2 C_2$$

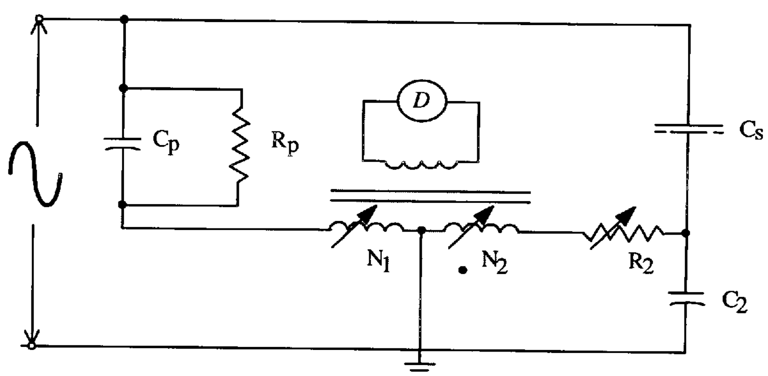


Figure 4—Measurement method—transformer ratio arm bridge basic circuit

6.2.3.5 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 constant 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 watts-loss 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 on 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 factors (tan δ_1) are measured. The test object is then connected to the high-voltage supply and the new capacitance (C_2) and dissipation factors (tan δ_2) are measured. The capacitance of the test object (C_x) is determined from

$$C_x = C_2 - C_1 \tag{18}$$

and

$$\tan\delta = \frac{C_2 \tan\delta_2 - C_1 \tan\delta_1}{C_2 - C_1} \tag{19}$$

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.

7. Tests with lightning impulse voltage

7.1 Terms used to characterize full lightning impulses

This subclause utilizes definitions that strictly apply to impulses without oscillations or overshoot, as shown in figure 5. If an impulse has oscillations or overshoot, the mean curve drawn through them as shown in figure 6 b) shall be used for interpretation. This mean curve may be created manually, by a piece-wise cubic spline smoothing algorithm, or by an exponential fitting algorithm.

7.1.1 Full lightning impulse

A full lightning impulse is a lightning impulse not interrupted by any type of discharge, as illustrated in figure 5.

7.1.2 Value of the test voltage

The value of the test voltage for a lightning impulse without overshoot or oscillations is its peak value.

The determination of the peak value in the case of overshoot or oscillations for a lightning impulse depends on the oscillation frequency or overshoot duration. If the oscillation frequency is less than 0.5 MHz or exceeds 1 μs, the peak value is taken as the maximum value of the recorded trace. If the oscillation fre-

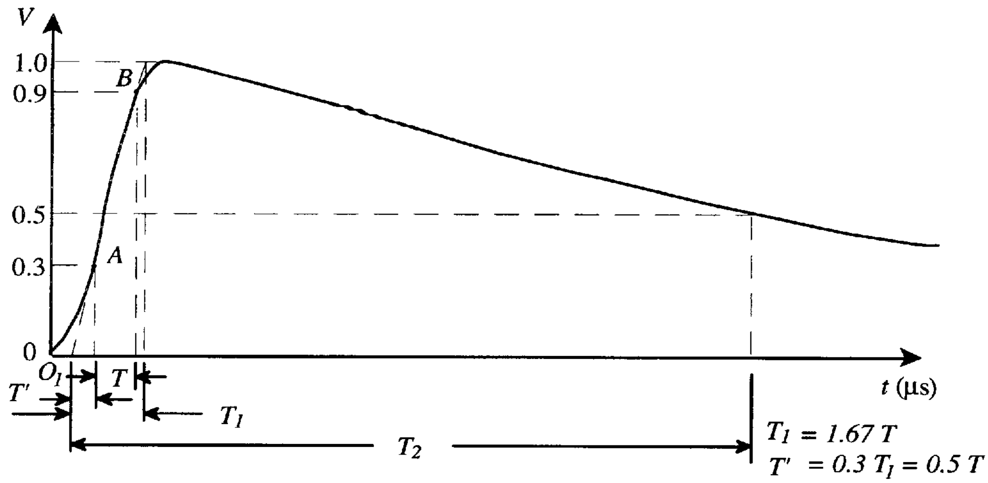


Figure 5—Full lightning impulse without oscillations or overshoots

quency is greater than 0.5 MHz or less than 1 µs, the peak value is determined from the maximum value of the mean curve, as shown in figure 6 b), or from the exponential fitting of the front and tail portions.

Permissible amplitude limits for the oscillations or overshoot on standard lightning impulses are given in 7.5.

For other impulse shapes, the appropriate apparatus standard should define the value of the test voltage, taking account of the type of test and test object. See figures 6 a) through 6 d) for examples.

7.1.3 Virtual front time (T_1)

The virtual front time (T_1) of a lightning impulse is 1.67 times the time interval between the instants when the impulse is 30% and 90% of the peak value, corresponding to points *A* and *B* in figure 5. If oscillations are present on the front, points *A* and *B* should be taken on the mean curve drawn through these oscillations.

7.1.4 Virtual origin (O_1)

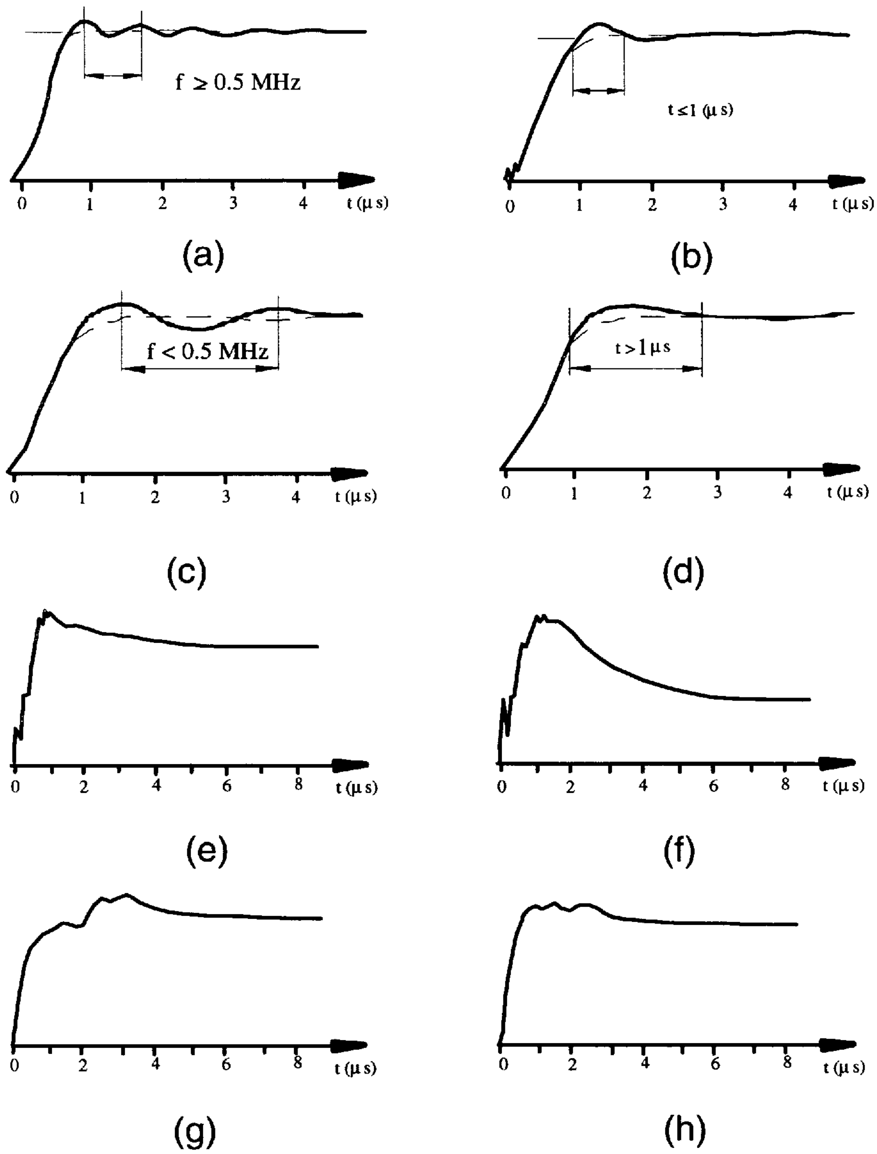
The virtual origin (O_1) of a lightning impulse is the instant preceding that corresponding to point *A* in figure 5 by a time 0.3 T_1. This is the intersection with the time axis of a straight line drawn through reference points *A* and *B* on the front.

7.1.5 Virtual time to half-value (T_2)

The virtual time to half-value (T_2) of a lightning impulse is the time interval between the virtual origin and the instant on the tail when the voltage has decreased to half of the peak value.

7.1.6 Standard lightning impulse

The standard lightning impulse is a full lightning impulse having a virtual front time of 1.2 µs and a virtual time to half-value of 50 µs. It is described as a 1.2/50 impulse.



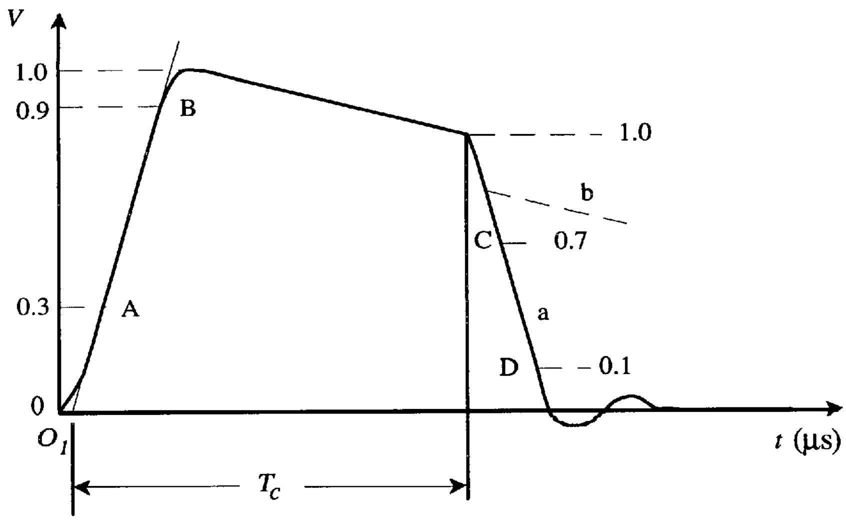
For figures a) and b)—The value of the test voltage is determined by a mean curve (broken line).
For figures c) and d)—The value of the test voltage is determined by the peak value.
For figures e), f), g), and h)—No general guidance can be given for the determination of the value of the test voltage.

Figure 6—Examples of lightning impulses with oscillations or overshoots

7.2 Terms used to characterize chopped lightning impulses

Generally, chopping of an impulse is characterized by an initial discontinuity, decreasing the voltage, which then falls toward zero with or without oscillations as shown in figure 7.

NOTE—With some test objects or test arrangements, there may be a flattening of the peak or a rounding off of the voltage before the final voltage collapse. Similar effects may also be observed due to imperfections of the measuring system.



a—Chopped wave caused by a disruptive discharge.
b—Chopped wave caused by a nondisruptive discharge.

Figure 7—Lightning impulse chopped on the tail

7.2.1 Chopped lightning impulse

A chopped lightning impulse is a prospective full lightning impulse during which any type of discharge causes a rapid collapse of the voltage. The collapse of the voltage can occur on the front, at the peak, or on the tail, as shown in figure 7.

An intentionally chopped lightning impulse can be generated by using a chopping gap (such as a rod gap described in clause 17, 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.

7.2.2 Instant of chopping (chop time) for tail-chopped impulses

The intersection of the 10%–70% line on the chop and the tail of the wave is shown in figure 7.

7.2.3 Voltage at the instant of chopping

The voltage at the instant of chopping is the voltage at chop time.

7.2.4 Time to chopping (T_c)

The time to chopping, T_c, is the time interval between the virtual origin and the instant of chopping.

7.2.5 Characteristics related to the voltage collapse during chopping

The characteristics of the voltage collapse during chopping are defined in terms of two points, C and D, at 70% and 10% of the voltage at the instant of chopping, as shown in figure 7.

NOTE—The use of points C and D is for definition purposes only. It is not implied that the duration and steepness of chopping can be measured with any degree of accuracy using conventional measuring circuits.

During chopped lightning impulse tests, the gap used for chopping shall be located as close as possible to the terminals of the test object without disrupting its electric field distribution. The impedance of the chopping circuit shall be minimized by the use of the shortest possible leads to the chopping gap. If the undershoot during chopping exceeds 50% of the voltage at the instant of chopping, the distances can be increased but should not exceed a lead length greater than the height of the test object.

7.2.6 Standard chopped lightning impulse

A standard chopped lightning impulse is a standard impulse that is chopped by an external gap after 2–5 µs. Other times to chopping may be specified by the appropriate apparatus standard. Because of practical difficulties in measurement, the virtual duration of voltage collapse has not been standardized.

7.2.7 Linearly rising front-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 part of the front of the impulse between 50% and 90% amplitudes (designated E and F respectively in figure 8). The impulse is considered to be approximately linear if the front, from 50% up to the instant of chopping, is entirely enclosed between two lines parallel to the line E-F, but displaced from it in time by 0.05 T_r.

This impulse is defined by

a) The time to chopping, T_c, which is the time after point F where the slope of the voltage wave becomes and stays negative
b) The voltage at the instant of chopping
c) The rise time, T_r, which is the time interval between E and F multiplied by 2.5
d) The virtual steepness, S, which is the slope of the straight line E-F, usually expressed in kilovolts per microsecond

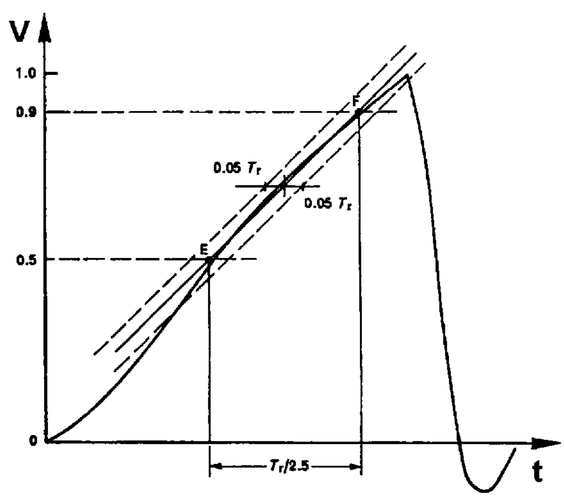


Figure 8—Linearly rising front-chopped impulse

7.3 Special lightning impulses

In some cases, oscillating lightning impulses may be applied. This offers the possibility of producing impulses with shorter front times, or with peak values corresponding to a generator efficiency greater than unity.

The impulse is considered to be approximately linear if the front, from 50% amplitude up to the instant of chopping, is entirely enclosed between two lines parallel to the line E-F, but displaced from it in time by 0.05 T_r.

7.4 Voltage/time curves

7.4.1 Voltage/time curves for linearly rising impulses

The voltage/time curve for impulses with fronts rising linearly is the curve relating the voltage at the instant of chopping to the rise time, T_r. The curve is obtained by applying impulses with approximately linear fronts of different steepness.

7.4.2 Voltage/time curves for impulses of constant prospective shape

The voltage/time curve for impulses of constant prospective shape is the curve relating the disruptive discharge voltage of a test object to the time to chopping, which may occur on the front, at the peak, or on the tail. The curve is obtained by applying impulse voltages of constant shape but with different peak values, as shown in figure 9.

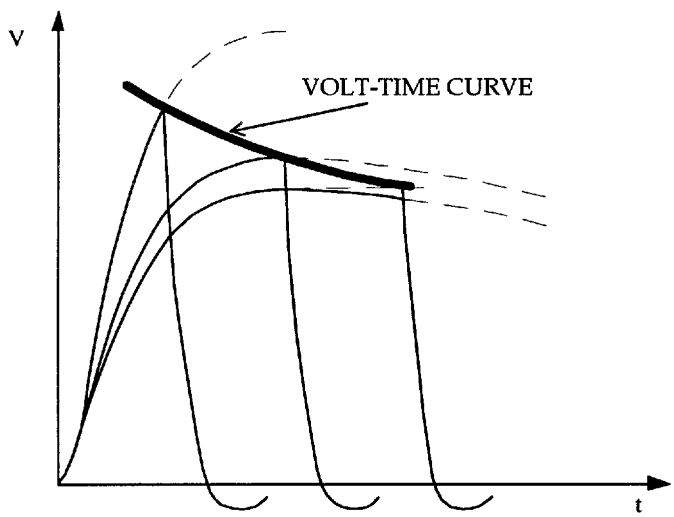


Figure 9—Voltage/time curve for impulses of constant prospective shape

7.5 Tolerances

If not otherwise specified by the appropriate apparatus standard, the following differences are accepted between values for the standard impulse and those actually recorded:

a) Peak value ±3%
b) Virtual front time ±30%
c) Virtual time to half-value ±20%

The impulse should be essentially unidirectional, but see Note 2 below. With some test circuits, oscillations, or an overshoot, may occur at the peak of the impulse, as shown in figures 6 a) through 6 d). If the frequency of such oscillations is greater than 0.5 MHz, or if the duration of overshoot is less than 1 μs, a mean curve should be drawn, as in figures 6 a) and 6 b). For the purpose of measurement, the maximum amplitude of this curve is chosen as the peak value defining the value of the test voltage.

Overshoot or oscillations in the neighborhood of the peak are tolerated, provided that their single-peak amplitude is not larger than 5% of the peak value. Measurement shall be made by a system with an upper limit frequency, f_2, not less than the value f_{max} given by

$$f_{max} = \frac{75}{2H} \tag{20}$$

where

H is the mean height of the loop formed by the generator and the nearest load capacitor (in meters)
f_{max} is the frequency (in megahertz)

However, f_2 need not be greater than 25 MHz. An auxiliary system that meets the above requirements can be used for measuring oscillations at a lower voltage if necessary.

In commonly used impulse generator circuits, oscillations on that part of the wavefront during which the voltage does not exceed 90% of the peak value have generally negligible influence on test results. If the appropriate apparatus committee finds these are of importance, it is recommended that their amplitudes be under the straight line drawn through the points A'B' in figure 10. These points are taken on the verticals of, respectively, the points A and B determined according to this clause, the distance AA' being equal to 25% and BB' being equal to 5% of the peak value. An auxiliary system that meets the above requirements can be used for measuring oscillations at a lower voltage if necessary.

NOTES

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 errors, which are the differences between values actually recorded and true values. For more information on measuring errors, see 13.6.

2—In specific cases, such as during tests on low impedance objects or on 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 have to be dealt with by the appropriate apparatus standard.

7.6 Generation of the test voltage

The impulse is 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.

7.7 Measurement of the test voltage and shape

7.7.1 Measurement with devices approved under clause 12

The measurement of the peak value, the time parameters, and the overshoot or oscillations on the test voltage should, in general, be made with devices that have passed the approval procedure referred to in clause 12. The measurements should be made with the test object in the circuit and, in general, the impulse shape should be checked for each test object. Where a number of test objects of identical design and size are

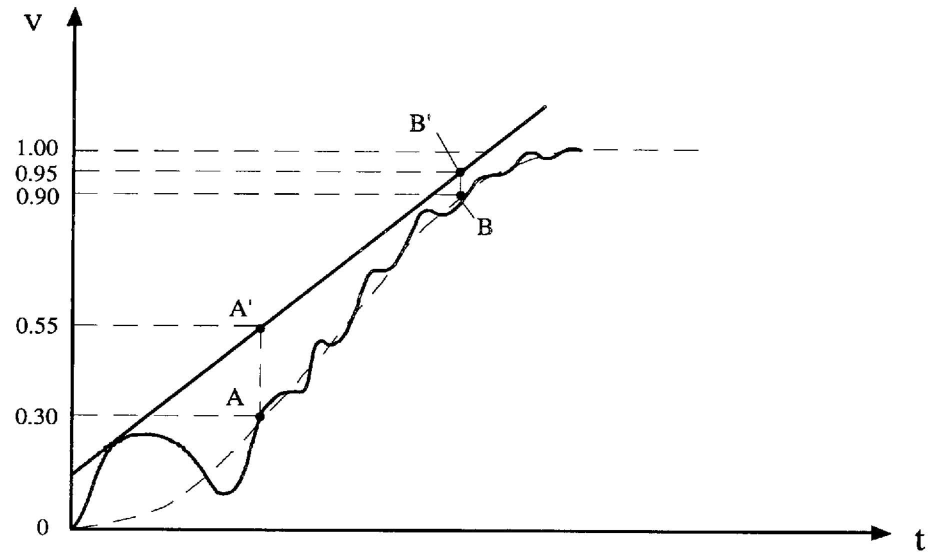


Figure 10—Maximum permissible amplitude of oscillations on the wavefront

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.

7.7.2 Measurement with a sphere gap in accordance with clause 17

The measurement of peak value only of full impulses or impulses chopped after the peak can be made with a sphere gap. The procedure usually consists in establishing a relationship between the spacing at which disruptive discharges occur and some other circuit variable related to the test voltage, such as the charging voltage of the impulse generator or the voltage from a divider.

The relationship may be dependent on the presence of the test object, the sphere gap, etc. Hence, it is important that these conditions are the same during the sphere-gap calibration and the actual test, except that, during the test, the sphere gap may be opened sufficiently to prevent sparkover.

The calibration shall be made in the range of 50–100% of the test voltage. Extrapolation from the highest calibration voltage to the test voltage is permissible if it can be shown that the test voltage is proportional to the related quantity.

7.8 Test procedures

The test procedure applicable to particular types of test objects (for example, the polarity to be used, the preferred order if both polarities are to be used, the number of applications, and the interval between applications) should be specified by the appropriate apparatus standard with regard to such factors as

a) The required accuracy of test results
b) The random nature of the observed phenomenon and any polarity dependence of the measured characteristic
c) The possibility of progressive deterioration of the test object with repeated voltage applications

Some guidance on the statistical aspects is given in clause 19.

7.8.1 50% disruptive discharge voltage test

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

a) The multiple level method, with *n* being greater than or equal to four voltage levels and *m* being greater than or equal to ten impulses per level
b) The up-and-down method, with *m* equal to one 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 are given in clause 19.

7.8.2 Rated withstand voltage tests

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

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

7.8.2.1 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 appropriate apparatus standard.

NOTE—This procedure is recommended for tests on degradable or nonself-restoring insulation.

7.8.2.2 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 nonself-restoring insulation is obtained by the detection methods specified by the appropriate apparatus standard.

7.8.2.3 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 more than one disruptive discharge occurs, the test object has failed to pass 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 nonself-restoring part of the insulation is observed with the detection methods specified by the appropriate apparatus standard during any part of the test, the test object has failed to pass the test.

7.8.2.4 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 clause 19.

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

$$V_{10} = V_{50}(1 - 1.3z) \qquad (21)$$

where

z is the conventional deviation of the disruptive discharge probability distribution

The appropriate apparatus standard shall specify the value to be assumed for z. For dry tests on air insulation, without any other insulation involved, the per unit value $z = 0.03$ can be used.

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 1.5–3% of the estimated value of V_{50}.

7.8.3 Assured disruptive discharge voltage test

The procedure for an assured discharge voltage test are similar to those described in 7.8.2, with the appropriate changes between discharge and withstand conditions.

The appropriate apparatus committee may also specify other procedures for specific test objects.

8. Tests with switching impulse voltage

8.1 Terms used to characterize switching impulses

8.1.1 Switching impulse

A switching impulse (as distinct from a lightning impulse) is defined in clause 3. The characteristics of a switching impulse are expressed by the parameters defined in 8.1.2 to 8.1.7 and illustrated in figure 11.

Additional parameters can be specified by the appropriate apparatus standard when considering specific tests.

8.1.2 Value of the test voltage

If not otherwise specified by the appropriate apparatus standard, the value of the test voltage is its peak value.

8.1.3 Time to peak (T_p)

The time to peak, T_p, for double exponential impulses is defined by

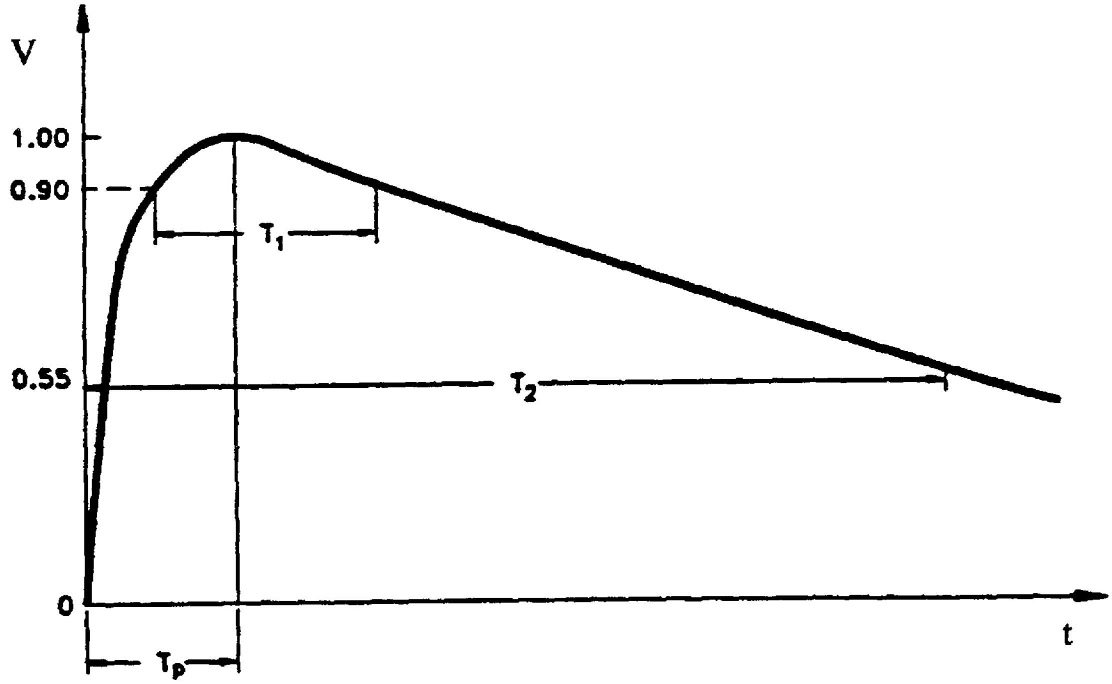


Figure 11—Full switching impulse

$$T_p = KT_x \qquad (22)$$

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

$$K = 2.42 - 3.08\mathrm{E}-03\,(T_x) + 1.51\mathrm{E}-04\,(T_2) \qquad (23)$$

The parameter T_2, time to half-value, is discussed in 8.1.4.

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.

8.1.4 Time to half-value (T_2)

The time to half-value, T_2, is the time interval between the virtual origin and the instant on the tail when the voltage has first decreased to half the peak value.

8.1.5 Time above 90% (T_d)

The time above 90%, T_d, is the time interval during which the impulse voltage exceeds 90% of its peak value.

NOTE—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.

8.1.6 Time to zero (T_0)

The time to zero, T_0, is the time interval between the virtual origin and the instant when the voltage has its first passage to zero.

NOTE—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.

8.1.7 Time to chopping (T_c)

The time to chopping, T_c, of a switching impulse is the time interval between the virtual origin and the instant of chopping.

8.1.8 Standard switching impulse

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.

8.1.9 Special switching impulses

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 appropriate apparatus standard.

8.2 Tolerances

If not otherwise specified by the appropriate apparatus standard, the following differences are accepted between specified values and those actually recorded, both for standard and special impulses (see Note 1 in 7.5), provided that the measuring device meets the requirements of clause 12:

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

In certain cases (for instance, with low-impedance or magnetic test objects), it may be difficult to adjust the shape of the impulse to within the tolerances recommended. In such cases, other tolerances or other impulse shapes may be specified by the appropriate apparatus standard.

NOTE—The disruptive discharge voltage of long gaps in air may be influenced by both the time to peak and the time to half-value of a switching impulse. Therefore, for such test objects it is recommended that the applied switching impulse be characterized by its actual time parameters. Larger tolerances in the prospective time to half-value may be allowed in the case of a disruptive discharge occurring before or at the peak.

8.3 Generation of the test voltage

Switching impulses are usually generated by a conventional impulse generator (see 7.6). 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 nondisruptive discharge currents in the test object. Such currents can reach quite large values, especially during contamination tests on external insulation at high voltages or during wet tests. In test circuits with a 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.

8.4 Measurements of the test voltage and determination of the impulse shape

The measurement of the test voltage and the determination of the impulse shape should be made as described in 7.7. Sphere gaps are an approved measuring device for switching impulse voltages.

8.5 Test procedures

The test procedures are, in general, the same as for lighting impulse testing, and similar statistical considerations apply (see 7.8 and clause 19). Unless otherwise specified by the appropriate apparatus standard, the per unit conventional deviation of the disruptive discharge voltage for dry and wet tests on air insulation, without any other insulation involved, can be assumed to be $z = 0.05$. Larger voltage intervals may be used when applying the multiple-level or the up-and-down procedures.

NOTES

1—With switching impulses, disruptive discharges frequently occur at random times well before the peak. In presenting the results of disruptive-discharge tests, the relationship of discharge probability to voltage is generally expressed in terms of the prospective peak value. However, another method is also in use, in which the actual disruptive discharge voltage for every impulse has to be measured by analog oscilloscope or digital recorder; the probability distribution of the measured voltage values is then determined by the method described for Class 2 tests in clause 19.

2—When a discharge is initiated by a leader in air from a positively charged electrode, a disruptive discharge can occur from many places in the high-voltage circuit. Any disruptive discharge not occurring on the test object should be observed and shall be disregarded.

9. Tests with impulse current

9.1 Terms used to characterize impulse currents

9.1.1 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 (see 7.1.3 and 7.1.5).

The second type has an approximately rectangular shape and is defined by the duration of the peak and the total duration (see 9.1.6 and 9.1.7)

9.1.2 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 appropriate 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.

9.1.3 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 (points C and B as shown in figure 12). 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 figures 6 a) and 6 b)] or they should be derived from the value of the test voltage determined by its peak [see figures 6 c) and 6 d)].

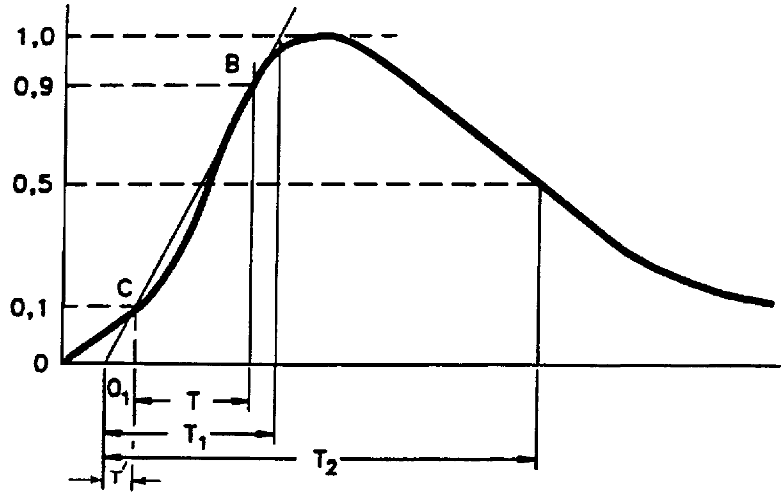


Figure 12—Exponential impulse current

9.1.4 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.

9.1.5 Virtual time to half-value (T_2)

The time to half-value, T_2, of an impulse current is the time interval between the virtual origin and the instant on the tail at which the current has decreased to half the peak value.

9.1.6 Duration of peak of a rectangular impulse current (T_d)

The duration of the peak of a rectangular impulse current, T_d, is the time during which the current is greater than 90% of the peak value as shown in figure 13.

9.1.7 Total duration of a rectangular impulse current (T_t)

The total duration of a rectangular impulse current is 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.

9.1.8 Standard impulse currents

Three commonly used impulse currents corresponding to the first type of impulse defined in 9.1.1 are used:

a) The 4/10 impulse with virtual front time of 4 μs and time of half-value of 10 μs
b) The 8/20 impulse with virtual front time of 8 μs and time to half-value of 20 μs
c) Rectangular impulse currents with durations of the peak of 500 μs, 1000 μs, or 2000 μs and total durations from 2000 μs to 3200 μs.

Other shapes may be defined by the appropriate apparatus standard.

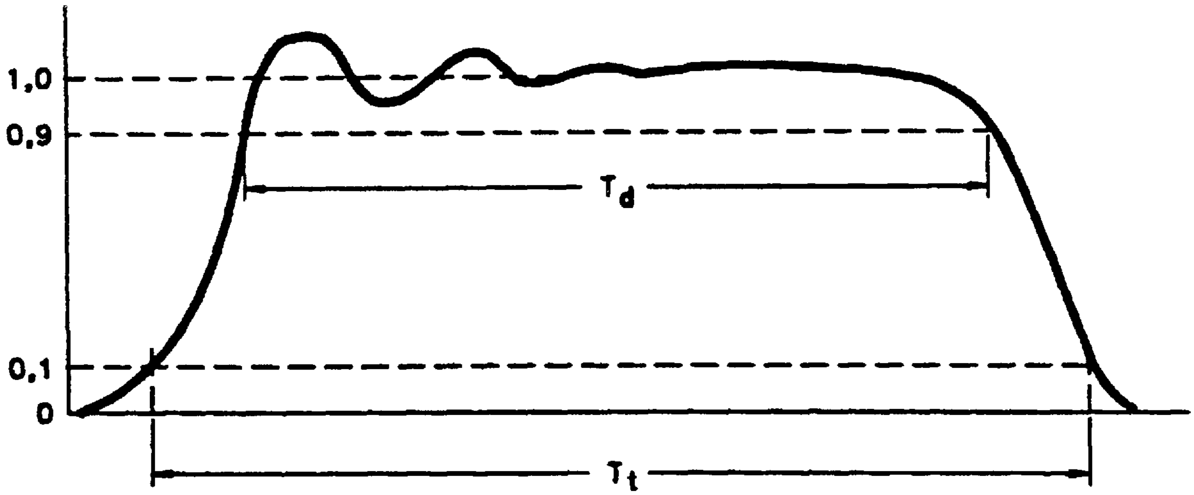


Figure 13—Rectangular impulse current

9.2 Tolerances

If not otherwise specified by the appropriate apparatus standard, tolerances are accepted between the following specified values for the impulse currents and those actually recorded, provided that the measuring system meets the requirements of clause 12.

For 4/10 and 8/10 impulses:

a) Peak value ±10%
b) Virtual front time (T_1) ±10%
c) Virtual time to half-value (T_2) ±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 should not be more than 20% of the peak value.

For rectangular impulses:

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

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 Measurement of the test current

The test current should be measured by a device that meets the requirements of clause 12.

9.4 Measurement of voltage during tests with impulse currents

Voltages developed across the test object during tests with impulse currents should be measured by any of the approved devices for measurement of impulse voltages listed in clause 12.

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.

10. Combined voltage tests

A combined voltage test is one in which two separate test sources are used to energize two separate terminals of the test object. The test sources may be of the same type or a combination of the ac, lightning impulse, switching impulse, or dc.

The test voltages are characterized by their amplitude, waveshape, polarity, and any time delay between the application of the two voltages. An example of a typical combined test circuit is shown in figure 14, along with the corresponding waveshape in figure 15. Definition of the applied waveshape is left to the appropriate apparatus standard. Measurement of the test voltage shall use an approved measuring device based on the requirements for the fastest and slowest waveshapes to be observed. In all cases, voltages are measured as referred to ground.

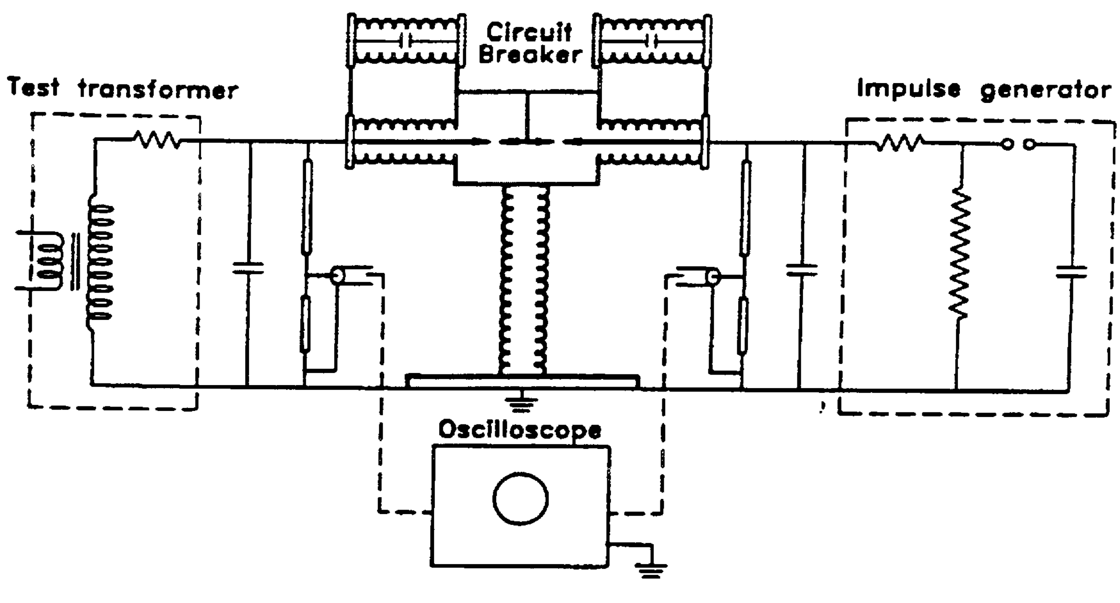


Figure 14—Typical test circuit for combined tests

The arrangement of combined test circuits shall take into account the possibility of a disruptive discharge during the test. In this case, it is possible to induce damaging stresses on the test equipment. Precautions shall therefore be taken to provide suitable protective devices (decoupling resistors, inductors, capacitors, or protective gaps) to protect the test sources.

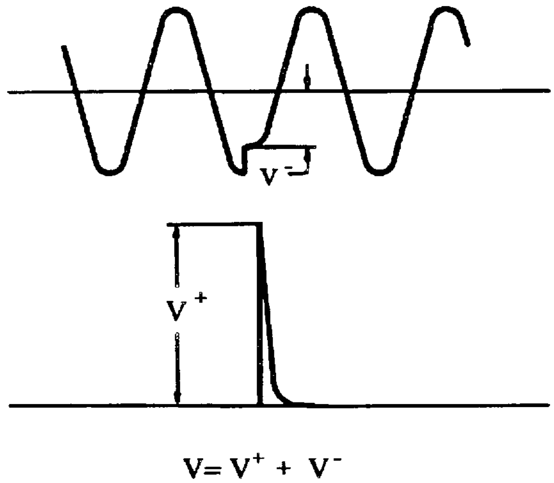


Figure 15—Voltage waves during combined voltage tests giving a value for the test voltage *V*

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

11. Composite tests

A composite test results when two different sources (voltage and/or current) are applied to the same terminal of a test object. Composite tests may be applied simultaneously, as in the case of dc bias tests with superimposed ac voltage, or with one source applied with a time delay, as in the case of an impulse voltage applied at a specific time on an object energized with ac voltage. Other combinations of test sources, including current sources, may be required. Specific requirements of composite tests are referred to in the appropriate apparatus standards.

As in the case of combined tests, approved measuring devices shall be used and care has to be taken to provide adequate protection of the test sources.

12. Measurement procedures

12.1 General

This clause is applicable to devices and complete systems, other than sphere gaps or rod gaps used for the measurement of voltages and currents during the dielectric tests with direct voltage, alternating voltage, impulse voltages, and for tests with direct, alternating, or impulse currents. Voltage measurements with sphere gaps and rod gaps are discussed in clause 17.

The objectives of this clause are to

a) Explain the terms used
b) State the requirements that the measuring systems shall meet
c) Describe some of the devices that are used

A measuring system that has been subjected to the performance tests and routine checks specified in this clause, and that has been shown to meet the requirements specified for a particular voltage or current measurement, shall be designated "an approved measuring system."

Specific guidance on such measuring systems and on methods for verifying their performance and accuracy are given in clause 13.

12.2 Principles

It is generally not practical to measure high voltages or high currents directly, and the usual procedure is to convert the quantity to be measured to a low voltage or current that can be handled with conventional measuring instruments.

Most of the measurements considered in this document cannot be made with a high degree of accuracy, and errors on the order of up to 3% or more have to be tolerated as indicated in the appropriate clauses. Some guidance for evaluating measurement errors is given in 13.6.

12.2.1 Measuring systems

A high-voltage or high-current measuring system generally comprises

a) A converting device: for example, a voltage divider, a high-voltage measuring impedance, or a 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

Such measuring systems, as well as those that utilize only some of the above components or that are based on different principles are also acceptable, provided that they meet the measurement requirements.

12.2.2 High-voltage or high-current converting devices

12.2.2.1 Voltage divider

A voltage divider is a device that is intended to produce accurately a suitable fraction of the test voltage for measurement. It usually has two impedances connected in series across which the voltage is applied. One of them, the high-voltage arm, takes the major fraction of the voltage. The voltage across the other, the low-voltage arm, is used for the measurement. The components of the two arms are usually resistors or capacitors (or combinations of these) and the device is described by the type and arrangement of the components.

12.2.2.2 Voltage transformer

A voltage transformer (also known as a potential transformer) is a step-down transformer designed for use in the measurement of the amplitudes and waveforms of high alternating voltages, usually at power frequency.

12.2.2.3 High-voltage measuring impedance

A high-voltage measuring impedance is a device that is intended to pass a small current that is proportional to the test voltage. It is connected in series with a current measuring instrument. It is made of resistors or capacitors, or combinations of these, but it should not be referred to as a voltage divider, although the elements are similar.

12.2.2.4 Current transformer

A current transformer is a device that is intended to produce accurately a current proportional to the test current. It usually consists of two or more magnetically coupled windings. It is used in the measurement of the amplitudes and waveforms of high alternating currents.

A wide-band current transformer can be used in the measurement of impulse currents. This device is usually designed with a voltage output for use with recording instrumentation.

A current comparator bridge is often used in conjunction with a specialized transformer, such as a zero flux transformer in which the magnetizing current is canceled by auxiliary circuitry. This system can be designed for the measurement of alternating or direct currents and has the advantage of higher ratio accuracy, small phase angle error, wide dynamic range, and dynamic stability.

12.2.2.5 Shunt

A shunt is a resistor that is intended to provide a voltage proportional to the current to be measured. It is usually provided with two pairs of terminals, one pair being used to carry the current to be measured while the other is used in measuring the voltage across the shunt.

12.3 Terms related to measurement

12.3.1 Scale factor of a measuring system

The scale factor of a measuring system is the factor by which the output indication is multiplied to determine the measured value of the input quantity or function. It is, in principle, a constant, but its validity may be restricted to a specific duration or frequency range, in which case the duration or frequency range for which it is valid shall be specified.

A linear system has a constant scale factor. The deviation from linearity is the amount of ratio error throughout the full test voltage or current range of the measurement system. Linearity measurements can be used to validate a scale factor that was obtained from a reduced voltage or current calibration, up to the full test voltage or current.

12.3.2 Voltage ratio of a voltage divider

The voltage ratio of a voltage divider is the factor by which the output voltage is multiplied to determine the measured value of the input voltage. It is dependent on the divider output terminal loading, and this impedance shall be stated. In principle, the ratio is constant, but its validity may be restricted to a specific duration, frequency range, or dynamic range, in which case the range for which it is valid shall be stated.

12.3.3 Response (*G*)

The response, *G*, of a measuring system is the output, as a function of time or frequency, when an input voltage or current is applied to the system.

12.3.4 Step response

The step response of a measuring system is the output as a function of time t when the input is a voltage or current step. A convenient form is the "normalized step response $g(t)$," in which the reference level of the output is normalized to unity.

12.3.5 Response time (T)

The response time, T, of a measuring system is indicative of the errors encountered when measuring rapidly changing voltages or currents and is given approximately by

$$T = \frac{(a_{\mathrm{i}} - a_{\mathrm{m}})}{\left[\frac{d}{dt}(a_{\mathrm{m}})\right]} \tag{24}$$

where

a_{i} is the value of a ramp input function at some specific time
a_{m} is the measured value of that quantity, provided that the rates of change of both the input function and the measured value of that function are constant and equal

NOTE—For particulars concerning the response time and related response parameters, see 13.4.

12.3.6 Transfer function $H(f)$

The transfer function $H(f)$ of a measuring system is equal to $Y(f)$ divided by $X(f)$, where $Y(f)$ and $X(f)$ are the frequency domain representations of the output and input signals respectively.

12.4 General requirements on measuring systems

The measuring accuracy and other characteristics of a measuring system shall comply with the requirements given in 12.5, 12.6, 12.7, or 12.8 according to the type of voltage or current to be measured.

12.4.1 Instrument characteristics

When standard types of instruments are employed, they should, where applicable, comply with ANSI C39.1-1981 and should be of class 0.5 or better. Other instruments, such as analog oscilloscopes and peak voltmeters, should comply with the general requirements for measuring systems given in this standard. Digital recorders or digital oscilloscopes for impulse measurements should comply with the most recent edition of IEEE Std 1122-1987.

NOTE—Some general recommendations for oscilloscopes and peak voltmeters to be used for high-voltage measurements are given in 13.4.2.4. More specific recommendations are under consideration.

12.4.2 Performance tests

Compliance with the requirements in this standard shall be verified by performance tests such as those described in the appropriate parts of clause 13. The results and inherent accuracy of these tests shall be stated in a "record of performance" (see 12.4.3). This record should be retained by the user.

The performance tests usually need to be made only once, but if the system is modified in any significant respect, or if its performance is in doubt, they should be repeated in part or in full. For some of the tests, it is sufficient for the tests to be made on a single prototype device. Performance tests should determine in particular

a) The scale factor and linearity
b) The response characteristics relevant to the types of voltage or current to be measured

NOTE—Neighboring objects, objects carrying high current, variations in atmospheric conditions, and surface contamination may affect the scale factor, linearity, and response characteristics.

The scale factor and linearity may be determined by a two-step process. First, the measuring system scale factor is checked at a reduced voltage by instruments whose accuracies are traceable to national standards. Second, the linearity is demonstrated by comparing the output of the high-voltage measuring system against some other quantity that is proportional to the output voltage of the test source. A record is made of the scale factor variance between the voltage measuring system and the other quantity from the reduced voltage up to the full test voltage. Linearity is evaluated at the minimum and maximum test voltage or current, and at a minimum of three approximately equally spaced values between these extremes. The deviation from linearity shall not exceed 2% from its mean. The reduced voltage or current scale factor shall be determined with an error not to exceed 1%.

In principle, the characteristics specified in this clause should be determined for the complete measuring system. They may, however, be deduced from separate tests made on its individual components. When this is done, the methods by which they are determined and the results of each of the individual measurements shall be stated in the record of performance.

Alternatively, the performance of a measuring system for a particular test arrangement may be checked by direct comparison against another measurement system that meets the requirements of this standard, such as sphere gaps.

NOTE—Attention should be drawn to the fact that the measurements performed at low voltage or on individual components may not include various interaction effects that may exist in the real test circuit. Such effects may originate from the high-voltage source or from different components in the circuit other than by their terminals (mutual coupling, stray capacitances, etc.) In addition comparison with another measuring device may only demonstrate that the system is acceptable for the particular test arrangement and the type of test voltage or current being used.

12.4.3 Record of performance

In addition to the results of the tests specified in 12.4.2, the record of performance shall include a general description of the system, its components, its principal dimensions, and other relevant parameters. More specifically, information on the following characteristics should be given when practical:

a) Details of the type of ground system and of the high-voltage connection used during the performance tests
b) The length, diameter, and position of the high-voltage lead
c) The type, length, position, and terminating impedances of the measuring cable
d) The characteristics of the measuring instruments used in carrying out the performance tests
e) The response to high-frequency transient oscillations as a function of frequency and (for impulse measuring systems) the highest frequency (f_{max}) for which the system is suitable
f) The absence of corona that might lead to the loss of linearity at high voltage

12.4.4 Routine checks

It is recommended that tests be made periodically (six months to a maximum of one year), or on request in connection with a particular test, to ensure that the scale factor of the measuring system has not changed from the value determined in accordance with 12.4.2.

12.5 Measuring systems for direct voltage

12.5.1 Quantities to be measured and accuracies required

The general requirements for direct voltage measurements are as follows:

a) To measure the mean value of the test voltage with an error of not more than 3%
b) To measure the peak-to-peak ripple amplitude with an error not more than 10% of the actual ripple amplitude, or an error not more than 1% of the mean value of the direct voltage, whichever is larger

NOTE—In certain cases, it may be necessary to detect and measure transient components. No requirements for this are given in this subclause, but some guidance on dealing with impulse measurements may be obtained from 12.7 and 12.8.

12.5.2 Requirements of the measuring system

The requirements in 12.5.1 will be met if the system meets the general requirements of 12.4 and the specified performance tests show that

a) The voltage ratio of the voltage divider or the value of the high-voltage measuring impedance is stable and known with an error of not more than 1%
b) The frequency response of the system used for measuring ripple voltage is adequate and the scale factor is known to within 10% for frequencies from the fundamental of the ripple frequency up to five times this frequency

12.6 Measuring systems for alternating voltages

12.6.1 Quantities to be measured and accuracies required

The general requirements for alternating voltage measurement are as follows:

a) To measure the peak or rms value of the test voltage with an error of not more than 3%
b) To measure the amplitude of harmonics with an error of not more than 10%

12.6.2 Requirements of the measuring system

The requirements of 12.6.1 will be met if the system meets the general requirements of 12.4 and the specified performance tests show that

a) The voltage ratio of the voltage divider or voltage transformer, or the value of the high-voltage measuring impedance, is stable and known for the fundamental frequency with an error of less than 1%.
b) The frequency response of the system used for measuring harmonics is adequate and the scale factor is known to within 10% for harmonic frequencies to the n^{th} harmonic. For most systems, n may be taken as 7.

12.7 Measuring systems for lightning and switching impulse voltages

12.7.1 Quantities to be measured and accuracies required

Practical difficulties prevent the attainment of the same degree of accuracy of measurement for all types of impulse voltages. Consequently, the accuracy requirements for a measuring system are specified in terms of the type of impulse to be measured.

The general requirements for impulse voltage measurements are

a) To measure the peak value of full impulses and impulses chopped on the tail with an error not exceeding 3%
b) To measure the peak value of impulses chopped on the front with an error, which is dependent on the time to chopping, T_c, as follows:
   1) For $T_c > 2$ µs, $\delta \leq 3\%$
   2) For 0.5 µs $\leq T_c \leq 2$ µs, $\delta \leq 5\%$

   For times to chopping shorter than 0.5 µs, larger errors than 5% shall be permitted. However, no general guidance can be given to measure the time parameters that define the impulse shape with an error that does not exceed 10%, with the exception of those that define the virtual time of voltage collapse during chopping in a chopped impulse. For these time parameters, no specifications for accuracy are given because of the extreme difficulty of making accurate measurements of this phenomenon.

c) To measure oscillations on an impulse with sufficient accuracy to ensure that they do not exceed the permitted levels given in clause 7

12.7.2 Requirements of the measuring system

The requirements of 12.7.1 will be met if the system meets the requirements of 12.4 and the specified performance tests show that the specifications mentioned in the following subclauses are satisfied.

12.7.2.1 Accuracy of the scale factor

a) The voltage ratio of the voltage divider shall be stable and known with an error not exceeding 1%.
b) The scale factor of the analog oscilloscope, impulse recorder, or peak voltmeter (including attenuators or coupling devices) should be stable and known with an error not exceeding 2%.
c) The time scale of the analog oscilloscope or impulse recorder should be stable and known with an error not exceeding 2%.

12.7.2.2 Response requirements

The response time, T, of an impulse measurement system generally results in a systematic error, both in the measurement of the time parameters of an impulse and in the measurement of amplitudes of impulses chopped on the front. Since there is also a random error in the determination of the value of T, this creates an additional component of error in the measurement of the time parameters.

12.7.3 Maximum frequency to be recorded (f_{max})

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

$$f_{max} = \frac{c}{(4H_g + 4H_c)} \text{MHz} \qquad (25)$$

where

c is 300 m/s, the velocity of an electromagnetic wave in air
H_g is the height of the portion of the impulse generator being used (in meters)
H_c is the height of the front capacitor (in meters)

NOTE—The value of fmax is generally limited to 25 MHz for tests with lightning impulses. For switching impulses, the value of fmax is further limited by higher impedance of the impulse circuit.

12.8 Measuring systems for impulse currents

12.8.1 Quantities to be measured, accuracies required, and requirements of the measuring system

The general requirements for impulse current measurement are as follows:

a) To measure the peak value of standard current impulses with an error of not more than 3%
b) To measure the time parameters of current impulses with an error of not more than 10%
c) To permit the detection of oscillations superimposed on a current impulse

These requirements will be met if the system meets the general requirements of 12.4 and the performance tests specified show that

a) The resistance of the shunt or, alternatively, the ratio of the current transformer is stable and known with an error of not more than 1%, and
b) The response time of the system complies with the requirements set out in the following table:

Impulse to be measured	Requirements (ns)
4/10 μs	$T < 800$
8/20 μs	$T < 1600$
250–2000 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.

NOTE—Shunts should preferably be the coaxial tubular type described in clause 13. Shunts of other types, or other types of devices such as wide band transformers, may be used provided that they fulfill the requirements.

Guidance on methods for determining the response of shunts is given in clause 13. In general, the unit step response of shunts does not take the form of a damped oscillation.

13. Procedures to ensure accuracy in high-voltage measurements

13.1 General

High-voltage measuring systems are subject to many different sources of error that affect the accuracy of amplitude measurements and that, particularly during impulse tests, may also affect the accuracy of time measurements.

The number of different types of measuring systems are too numerous to mention in individual detail in this standard. The principal sources of error for various common arrangements of measuring systems are described in the following subclauses, together with techniques that have been found to be satisfactory for overcoming these errors. In general, the techniques require the determination of the scale factor by comparing the measuring system with another system (or device) that is known to be within the specified limits of accuracy up to the full test voltage or, alternatively, by determination of the scale factor at a reduced voltage together with a demonstration of linearity up to the full test voltage. The accuracies of instruments used for the determination of scale factor shall be traceable to national standards.

Clearances from the voltage divider to neighboring walls and high-voltage apparatus during tests shall be similar to those that were present during the measurement of the scale factor. Tests to demonstrate linearity shall be performed initially and once per year or after major repair. Measurements of scale factor should preferably be made at more frequent intervals (for example, once per month).

This clause is divided into four parts dealing with systems and devices for measuring high direct voltages, alternating voltages, lightning and switching impulse voltages, and impulse currents.

13.2 Measurement of direct voltages

13.2.1 General

The following clauses apply particularly to measurements made by means of voltage dividers. Measurements performed using instruments in series with high ohmic value resistors are not treated separately because they are similar to voltage dividers as far as direct voltages are concerned. Some information is also given concerning both electrostatic and generating voltmeters.

13.2.2 Ratio determination

The ratio of a resistive divider is normally determined from separate resistance measurements of the high-voltage (R_1) and low-voltage (R_2) arms of the divider. Such measurements are usually performed at relatively low voltage by means of a Wheatstone bridge or other resistance bridge of equivalent accuracy. The resistance of the high-voltage arm may also be measured at high voltage by means of a high-voltage Wheatstone bridge, providing that a high-voltage standard resistor is available for use in the reference branch of the bridge. Since the resistance (R_1) of the high-voltage arm may be 1000 MΩ or more, it may be difficult to measure its value with the required degree of accuracy at low voltage. In such a case, the resistances of the individual resistors comprising the high-voltage arm may be measured and the total resistance obtained by adding the individual resistance values. The ratio of a resistive divider may also be determined by comparison against a high-voltage resistor that has an accurately known scale factor.

13.2.3 Reference divider

The scale factor of a direct voltage measurement system also may be checked with a reference divider measurement system that has been calibrated with traceability to national standards. The reference divider should be rated for at least 20% of the maximum voltage to be measured by the system being calibrated. The reference divider is used by taking simultaneous measurements with the system under test. The scale factor is determined by taking at least one measurement, but tests at several voltage levels are preferred. The tests to determine the scale factor of a measurement system do not determine the linearity of the scale factor for the entire dynamic range unless the reference system is rated for the same voltage as the system being calibrated. If the reference system is rated for the maximum voltage to be used, then the linearity may be determined if calibration points are taken at the minimum and maximum of the dynamic range and at least three intermediate points. For systems that exhibit predictable nonlinearity, calibration curves may be provided to correct the indicated values to the correct values.

13.2.4 Possible sources of error and precautions

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 will cause a nonlinear characteristic and, if the low-voltage arm is unshielded, additional errors may arise due to the "pick-up" of ionic currents that flow through the surrounding air and that tend to concentrate in areas of high field strength.

Surface leakage and ionic currents can usually be intercepted by means of suitable guard and shield electrodes respectively.

13.2.5 Linearity

A technique for checking the linearity of a direct voltage divider involves its calibration against a rod gap, sphere gap, or a reference divider, as described in 17.6 and 17.7. If the maximum deviation from linearity results in an overall measuring error of less than 3% at any point over its specified voltage range, the divider is considered acceptable. If the error exceeds 3%, the cause of the nonlinearity has to be investigated and corrected.

When the divider is of modular construction, a check for possible errors caused by corona currents from intermediate electrodes at the test voltage may be performed by making simultaneous measurements of input and output currents. If these currents are equal, it may be assumed that errors from this source are negligible. However, it should be noted that equal input and output currents do not necessarily ensure linearity. The linearity may be demonstrated by calibration against a rod gap as described above or by demonstrating the linearity of each module by comparing it up to its rated voltage against two or more similar modules connected in series. Also, for direct voltage sources based on half-wave, full-wave, or cascade rectifier circuits, the peak value of the output voltage of the energizing transformer may be used as the comparative reference quantity because the output direct voltage from the source is proportional to this quantity to the degree of accuracy required by this standard. This test shall be performed with another resistive load besides the voltage divider on the voltage source in order to minimize ripple.

13.2.6 Transient response

Resistive dividers are usually inadequate to measure the ripple on the output voltage. In addition, for direct voltage test systems that require automatic control (for example, systems for pollution testing), the measuring system shall have a rapid transient response; a conventional resistive divider will not normally have a sufficiently rapid response. For such cases, a measuring system comprising a parallel connected resistance-capacitance network will usually provide an adequate high-frequency response that will meet the high-frequency requirements.

The transient response of an R-C divider is measured according to the procedures described in clause 12. No requirements can be specified for the response time because of the wide variety of test systems. Guidance has to be obtained from the manufacturer of the test system.

13.2.7 Electrostatic and generating voltmeters

13.2.7.1 Electrostatic voltmeter

An electrostatic voltmeter has two electrodes that are connected to the points between which the high voltage is to be measured. The electrostatic field between the electrodes generates an attracting 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.

13.2.7.2 Generating voltmeter

A generating voltmeter is a capacitive device, the input terminals of which are connected to the points between which the voltage is to be measured. It is essentially a variable capacitor, the capacitance being periodically changed between two fixed values. A measuring instrument together with a suitable switching or rectifying device measures the change of charge, which (in general) is proportional to the mean value of the direct voltage.

13.2.7.3 Calibration

Measuring systems of these types can be calibrated by comparison during parallel operation with other approved measuring systems.

13.2.7.4 Sources of error

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

13.3 Measurement of alternating voltages

13.3.1 General

Various methods as described in clause 6 are used to measure high alternating voltages. Potential transformers can be used over a range from a few kilovolts to a few hundreds of kilovolts and, since their accuracies are usually higher than that required by this standard, they will not be covered in the following clauses.

The following clauses apply mainly to the most commonly used methods of measuring high voltages, which are by means of capacitor type dividers or by measuring the rectified current through a capacitor. Some information is also given concerning both electrostatic and generating voltmeters.

13.3.2 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 certified, 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.

The ratio of a voltage divider may also be determined by comparing it against another certified, traceable measuring system. Potential transformers, reference capacitive dividers, or compressed-gas standard capacitors may be used as reference systems. However, if the test voltage waveform contains harmonics, the measurement of these harmonics by a potential transformer may be incorrect.

If the capacitive divider being calibrated is used at a higher voltage than that of the reference system, linearity shall be demonstrated up to that voltage.

13.3.3 Reference divider

The scale factor of an alternating voltage measurement system also may be checked with a reference divider measurement system that has been calibrated with traceability to national standards. The reference divider should be rated for at least 20% of the maximum voltage to be measured by the system being calibrated. The reference divider is used by making simultaneous measurements with the system under test. The scale factor is determined by making at least one measurement, but tests at several voltage levels are preferred. The tests to determine the scale factor of a measurement system do not determine the linearity of the scale factor for the entire dynamic range unless the reference system is rated for the same voltage as the system being calibrated. If the reference system is rated for the maximum voltage to be used, then the linearity may be determined if calibration points are taken at the minimum and maximum of the dynamic range and at least three intermediate points. For systems that exhibit predictable nonlinearity, calibration curves may be provided to correct the indicated values to the correct values.

13.3.4 Rectified current through a capacitor

Even if the test voltage waveform is heavily distorted, the rectified current method gives acceptable accuracy for the measurement of the peak voltage, provided that the waveform does not contain more than one peak during each half cycle. The waveform shall be checked by means of an oscilloscope to ensure that it meets this requirement.

If the supply to the test source is derived from a power system, the nominal system frequency may be considered to be sufficiently stable to meet the accuracy requirements of this standard. However, if a rotating machine is used to energize the test source, the accuracy and stability of its frequency shall be checked.

Due to the forward voltage drop across the diodes, a capacitive current will flow from the central conductor of the measuring cable to the surrounding cable sheath. This current is usually negligible in comparison to the current to be measured. However, if the cable is long (for example, greater than 100 m), the voltage drop due to the cable resistance may result in sufficient additional current flowing to the sheath to cause an error. Possible errors from this source should be investigated.

13.3.5 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 be due also to the inherent nonlinearity of the capacitor elements that were used in the construction of the divider.

Calibration against a sphere gap may be used to demonstrate linearity to within ±3%. However, if a suitable sphere gap is not available for calibration up to the rated voltage of the divider, some other technique has to be used. A suitable technique when a transformer is used as the test source is to establish the relationship between the transformer primary voltage and the test voltage. Note that the ratio of output voltage to primary voltage of the test transformer is not necessarily equal to its turns ratio. In addition, it may change with load capacitance. The voltage ratio of the test transformer may be determined from its input admittance and, consequently, once the admittance-ratio characteristic is known, the output voltage of the transformer may be readily determined, irrespective of the value of the load capacitance. The voltage ratio/input admittance characteristic is sufficiently linear for the purposes of this standard provided that the test transformer is operated within its designed voltage range. When transformers are operated in cascade, the uppermost transformer may be inadvertently excited to a level exceeding its rated voltage without exceeding the rated voltage of the cascade group. In such a case, the saturation of its core will cause the voltage ratio/input admittance characteristic to become nonlinear. In addition, the internal insulation of the transformer may be damaged. Therefore, care has to be taken to prevent this condition. A procedure to determine the voltage on the top transformer from the input admittance to the cascade group is given in the literature (see [B93]).

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 measurements may also be used as comparative systems when checking the linearity of alternating voltage dividers. The 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 is sought and hence the absolute value of the electric field is not required, thereby eliminating the need to calibrate the field strength meter. For linearity verification of voltage dividers, field 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 contents of such systems are typically less than 0.5%. These instruments are also recommended for voltage measuring systems based on measurements of rectified current through a capacitor.

13.3.6 Determination of the amplitude-frequency response of a measuring system

To determine the amplitude-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.

In an alternative technique, 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.

The transfer function [$H(f)$] 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 technique 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.

13.3.7 Possible sources of errors and precautions

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 its overall length 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 that should be suitably protected.

13.4 Measurement of impulse voltages

13.4.1 General

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 a good transient response. This clause deals with methods for evaluating the response characteristics and errors of impulse voltage measurement systems. The response characteristics shall be determined by simultaneous measurements of actual test impulse voltages made with the measurement system to be evaluated and a reference divider measurement system that meets the requirements of this standard.

The measuring system shall not load the voltage generator so heavily that the impulse waveshape is significantly distorted and the generator is prevented from developing the required high rates of change of voltage across the test object.

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

13.4.2 Measuring system components

Most high-voltage impulse measuring systems (except sphere gaps) consist of a voltage divider; an impulse oscilloscope, an impulse digitizer, an indicating instrument, or a combination of these; a high-voltage lead; low-voltage measuring cable; and a ground return circuit. A high-voltage lead damping resistor may also be included. Important features of these components are explained in the following subclauses. Other high-voltage measuring devices, such as an electro-optic Kerr cell or Pockels cell, are also used. These electro-optic devices have optical properties that change when voltage is applied. In general, they have a fast response and provide more immunity to electromagnetic interference than do voltage dividers; however, they are not normally used for industrial testing.

13.4.2.1 Voltage divider

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.

The effect of stray capacitance can be reduced in resistive dividers by keeping the resistance as low as possible without unduly loading the impulse generator and by using shielding electrodes at the high-voltage end of the divider. These electrodes provide a capacitive path for charging the stray capacitance to ground. In capacitive dividers, the capacitance of the divider should be large enough to minimize the effect of stray capacitance. When purely capacitive dividers are used to measure rapidly changing impulses, they may have large overshoots or oscillations in their output due to parasitic inductances in the low-voltage arm. Mixed dividers consist of both capacitive and resistive elements. In such dividers, the effect of stray capacitance depends on the manner in which the component parts are connected.

13.4.2.1.1 Measurement of the divider ratio

Divider ratios are usually determined by measuring the impedances of the high-voltage and low-voltage arms separately. The ratio is then obtained by dividing the sum of the impedances by the impedance of the low-voltage arm. An alternative technique consists of applying a known voltage to the high-voltage terminal of the divider and simultaneously measuring the voltage across the low-voltage arm. The ratio is determined by dividing the input voltage by the output voltage. For resistor dividers, the resistances of the high-voltage and low-voltage arms are usually measured with a low direct voltage by means of a Wheatstone bridge or by means of an ohmmeter providing it is of equivalent accuracy. The ratios of capacitor-type dividers are affected by stray capacitance; therefore, their ratios should be determined with the high-voltage arms positioned in the locations normally occupied during the tests. For capacitor or series resistor/capacitor dividers, the capacitance of the high-voltage arms may be measured by means of a Schering bridge or a transformer ratio-arm bridge. The use of a low-voltage general-purpose RLC bridge is not recommended because lead and stray capacitances will be included in the measurements and the resulting ratio will therefore be in error. For parallel resistor/capacitor dividers, the resistance and capacitance of the high-voltage arms are usually measured by temporarily removing the resistors from the high-voltage arm and measuring the capacitance of the remaining column using the technique described above. The resistance of the high-voltage arm is measured either in situ or when the resistors have been temporarily removed from the capacitor column. As in the case for resistive dividers, a Wheatstone bridge is used for this measurement. The ratios of the resistances and capacitances in the two branches of the divider should be equal to one another. If the resistors cannot be removed from the high-voltage arm, the ratio may be determined by measuring the ratio of the resistive branch with a Wheatstone bridge and subsequently checking the response of the complete divider to a square wave and determining the ratio after the divider response has settled.

13.4.2.2 High-voltage lead

The length, position, and diameter of the lead connecting the high-voltage terminal of the test object may influence the performance of the measuring system. 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.

Ideally, the diameter of the lead should be large enough to prevent corona since corona on the lead can affect the performance of the measuring system. When corona cannot be prevented, a small diameter lead, which produces glow corona and avoids streamers, is normally used. Vigorous streamer or leader discharges in the vicinity of the divider should be avoided.

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 in the measurement of the inductive voltage drop in this lead.

13.4.2.3 Damping resistor

A resistor of very low inductance may be inserted in the high-voltage lead 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 voltage-divider ratio of the system is determined.

13.4.2.4 Analog oscilloscope/digital recorder

The output of the voltage divider may be recorded with an analog oscilloscope or digital recorder having adequate bandwidth to measure the required impulses, with an impulse oscilloscope, or with an impulse digitizer. The output of the voltage divider may be further attenuated at the oscilloscope end of the measuring cables either externally, internally, or both. The additional attenuation shall also be taken into account when determining the overall scale factor. Precautions have to be taken to shield the oscilloscope properly to prevent pickup of external disturbances, including those arising from the impulse generator.

An impulse oscilloscope is essentially a well-shielded instrument with a high writing speed and with a single-sweep time base that can be triggered in synch with the impulse. The high-voltage supplies of the instrument should be stabilized and have practically no ripple. Means of calibrating the sweep speed and the voltage deflection sensitivity should be provided. Provisions should also be made for photographic recording of the oscillograms.

It is important that the deflection plates of the oscilloscope remain under the same conditions of grounding and biasing during the calibration and during the recording of the impulse voltages. Impulse oscilloscopes are not normally equipped with amplifiers, and the leads to the deflection plates are kept as short as possible to obtain good high-frequency performance.

Low-voltage analog and digital oscilloscopes are also used, provided that they have adequate bandwidth and voltage-measuring accuracy for the impulses to be measured. They are especially sensitive to electromagnetic interference. Therefore, special care should be taken to ensure that the oscilloscope is properly shielded from these disturbances.

The impulse recording system is normally provided with an input connector for the coaxial cable from the voltage divider. The input impedance as measured at this conductor should either match the characteristic impedance of the coaxial cable or be as high as possible, depending on the type of the divider (see 13.4.2.6). Sometimes, provisions are made for both possibilities to be met.

It is important to check the overall scale factor, the stability, the response characteristics, and sensitivity to external disturbances of both oscilloscopes and peak-reading voltmeters.

An impulse digitizer is a specialized, well-shielded digital recorder or digital oscilloscope used for measurements of high impulse voltages or high impulse currents. It is an instrument that can make a temporary digital record of a scaled high-voltage or high-current impulse and then convert this temporary digital record to a permanent record. The permanent digital record is displayed on the instrument or on an accompanying computer as an analog graph. The performance requirements that a digital impulse recorder shall meet are presented in the most recent version of IEEE Std 1122-1987.

13.4.2.4.1 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 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 0.1 μs 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 approximately 1 ns or 2 ns.

13.4.2.4.2 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 IEEE Std 1122-1987. Whichever technique is used, the probe signal should agree with the external voltmeter or the impulse calibrator to within 1.0%.

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 1.0% for measurements of time parameters.

13.4.2.4.3 Oscilloscope deflection

In order to achieve the maximum accuracy during impulse measurements, the divider ratio and oscilloscope attenuation factor should be adjusted so that the signal deflection occupies almost the full screen. On an 8 boscilloscope this will result in an amplitude uncertainty of approximately 0.5%. If only half-full screen deflection is used, the uncertainty will increase to 1.0%, and, if smaller deflections are used, the uncertainties will be even greater. These uncertainties may be reduced by using a 10 b or a 12 b oscilloscope, but the sampling rate should be fast enough to measure the front time of a standard lightning impulse accurately. A minimum sampling rate of 60 million samples per second (sampling time less than or equal to 17 ns) is required in order to measure the fastest standard lightning impulses (see IEEE Std 1122-1987).

The oscilloscope itself, including its internal attenuator, should be checked for accuracy, preferably by means of a digital oscilloscope calibrator (see IEEE Std 1122-1987). When two or more channels are being used during comparative measurements, the check described above for probes or internal dividers should also be used for all channels involved. The measured waveforms should agree to within 0.5% for amplitude measurements and to within 1.0% for measurements of time parameters.

13.4.2.4.4 Accuracy of time measurements

Internal clocks in modern digital oscilloscopes are sufficiently accurate and stable so that errors from this source are almost nonexistent. If there are doubts concerning the time axis of an instrument, a check of its accuracy and linearity can be performed by applying a 10 MHz sinusoidal signal from an external signal generator. The uncertainties for the measurements thus obtained should lie within the range specified by the manufacturer for the instrument under test (see IEEE Std 1122-1987).

13.4.2.5 Peak-reading voltmeter

The peak-reading voltmeter is an instrument that usually functions by charging a capacitor, through rectifiers, to a voltage that is proportional to the peak value of the impulse to be measured. The charge is retained on the capacitor and is read by means of a very high impedance amplifier plus a recording or indicating instrument that is incorporated into the device. Such a device has an error that depends on the shape of the impulse to be measured and should be determined experimentally. The input impedance of the instrument is subject to the same restrictions noted for the oscilloscope. It should be noted that most instruments of this type have been found to be very sensitive to interference, especially when measuring impulses that are sharply chopped.

13.4.2.6 Coaxial cable and matching devices

Various methods may be used to terminate measuring cables satisfactorily depending on the type of voltage divider being used. The circuits shown in figure 16 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. The dielectric loss of the insulation, the resistance of the inner conductor of the cable, and the resistance of the sheath may introduce errors. It is essential that the cables be matched at one or both ends to prevent multiple 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 as shown in figure 16 b). 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 [figure 16 c)]. Any attenuator or connecting device inserted in the cable should have as high an input impedance as possible. Other methods of matching may be used, provided that the response of the system meets the requirements specified in 13.4.9.

13.4.2.7 Ground returns

There are normally several points in the generating and measuring systems that are interconnected and connected to the ground terminal of the test object. It is important that the impedance between all of these points be kept to a minimum. Special care has to be taken to minimize the impedance to ground at any point in the test circuit where there are high ground currents, such as at the ground terminals of the test object, impulse generator, and front capacitor. 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.

13.4.3 Determination of voltage ratios and scale factors

The scale factor of a measuring system is usually obtained by multiplying the voltage ratio of the divider by the sensitivity of the instrument. This sensitivity is determined by conventional methods. Alternatively, the scale factor of the measuring system can be determined through direct comparison of the voltage measurement system with a reference system meeting the requirements of this standard.

Various methods are available for the determination of the ratio:

a) By calculation of the ratio based on the measurement of the impedance of the individual components.
b) By simultaneous measurements of the input and output voltages of the divider.
c) By the use of sphere gaps.
d) By the use of some form of bridge circuit in which the output of the divider is balanced against the output of an accurate adjustable divider. This method can be more accurate than the three former methods.

The voltage ratio of a divider is usually determined at low voltage. For resistive dividers, measurements can be made according to item b) or item c) with either alternating or direct voltage. For capacitive dividers, alternating voltages are used. To check that the determined ratio is applicable within a given frequency range, it is recommended that the ratio be determined at two or more frequencies; for example, at power frequency and at 1 kHz.

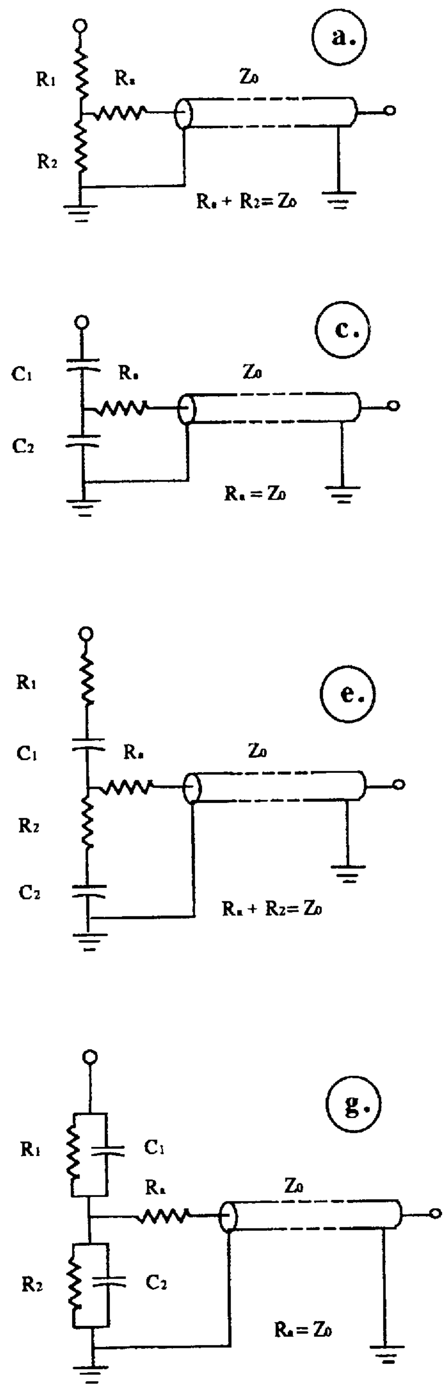


Figure 16—Methods of matching coaxial cables

It is also necessary to ensure that the voltage divider ratio remains constant to within 1% for times after the start of the measured voltage impulse near the times to crest, and that this ratio does 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.

With dividers of the capacitor or mixed type, it is generally necessary to check the scale factor of the system in the actual test arrangement to verify the voltage ratio, even though this ratio has been determined independently. This is because the presence of stray capacitances can affect the voltage ratio. Moreover, the ratio measured with a low-frequency alternating voltage may differ from that applicable when measuring impulse voltages.

A suitable method for checking the overall scale factor is to make simultaneous measurements using two systems—the system to be checked and one involving either a suitable resistive divider or some other measuring system that meets the requirements of this standard. In the check, an impulse voltage of the type to be measured should be used. The test may be done at a voltage level well below the rated voltage of the system being checked; thus, a resistive divider or another measuring system meeting the requirements of this standard of relatively low-voltage rating may be used. However, it should be recognized that the voltage ratio determined at low voltage may differ from that applicable at high voltage if there are voltage-dependent effects in the measuring system, such as corona.

13.4.4 Qualification of an impulse measuring system

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 in clause 12 of this standard *and*

a) Have step response parameters that meet the criteria in table 1 *or*
b) Have an adequate transient response for the waveshape in question as demonstrated by convolution techniques

Table 1—Step response time parameters of the reference divider (in nanoseconds)

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

*The T_s requirement does not apply in the case of resistor reference dividers.

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

13.4.5 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 17. The step generator has to have approximately zero impedance while generating the step and during the subsequent response, and comprises some form 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.

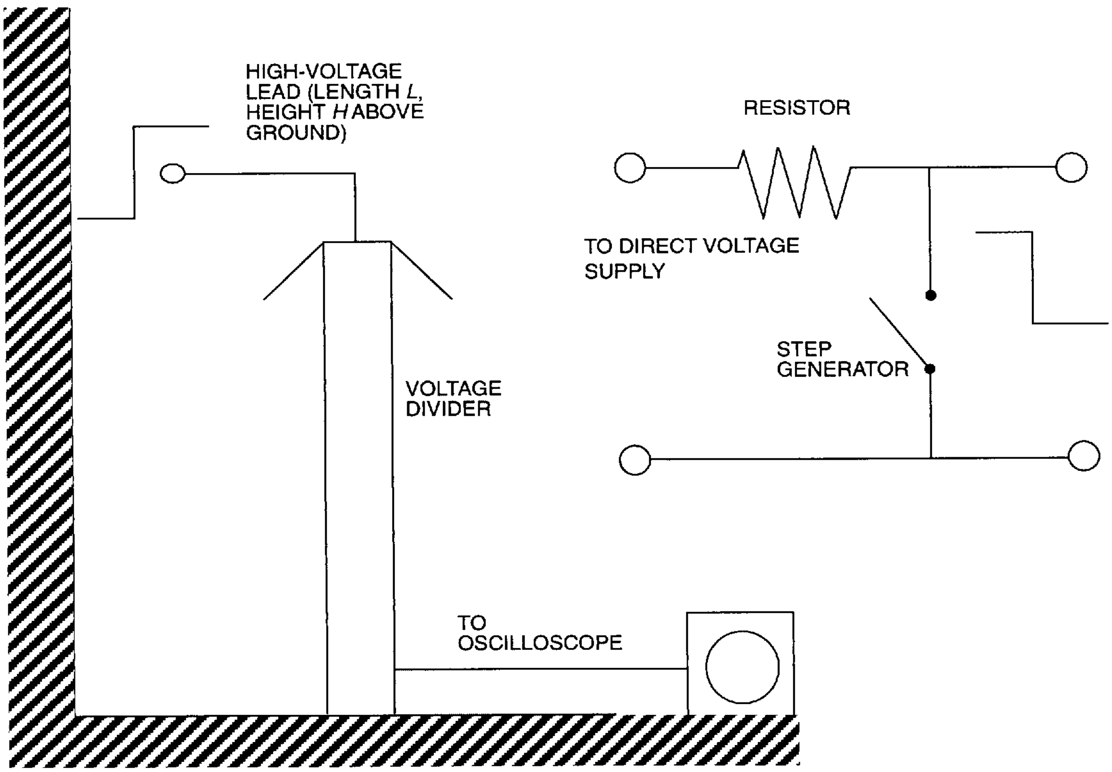


Figure 17—The experimental step response method

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 10–15 μs 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 pressure; this may eliminate the need for amplification and thus permit the use of the normal impulse oscilloscope.

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.

13.4.6 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 18.

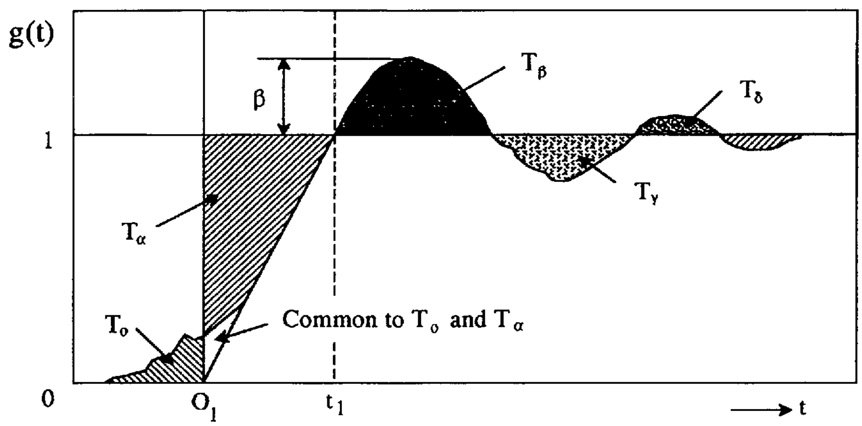


Figure 18—Definitions of response parameters with respect to the normalized experimental step response *g(t)*

In order to establish the response parameter, a virtual origin (O_1) has to be determined. A procedure for doing this is given in 13.4.6.1. 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.

13.4.6.1 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 13.6.4). The solution to this problem should consider two points. First, the noisy front part of 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. How to draw this "mean curve" is discussed in this subclause since it causes confusion and controversy. 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% point, will be smaller than the one 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 thus be determined by the intersection of the time axis and a line that passes through the 10% and 90% points.

13.4.6.2 Determination of the experimental response time (T_N)

The approximate step response time (T_N), known as the experimental response time, is found from

$$T_N = T_\alpha - T_\beta + T_\tau - \ldots\ldots \quad (26)$$

where

T_α, T_β, T_τ are the shaded areas in figure 18

13.4.6.3 Determination of the settling time (t_s)

The setting 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 the equation

$$\left| \int_{t_s}^{\infty} [1 - g(t)]\, dt \right| < 0.02 t_s \quad (27)$$

and is also illustrated in figure 19.

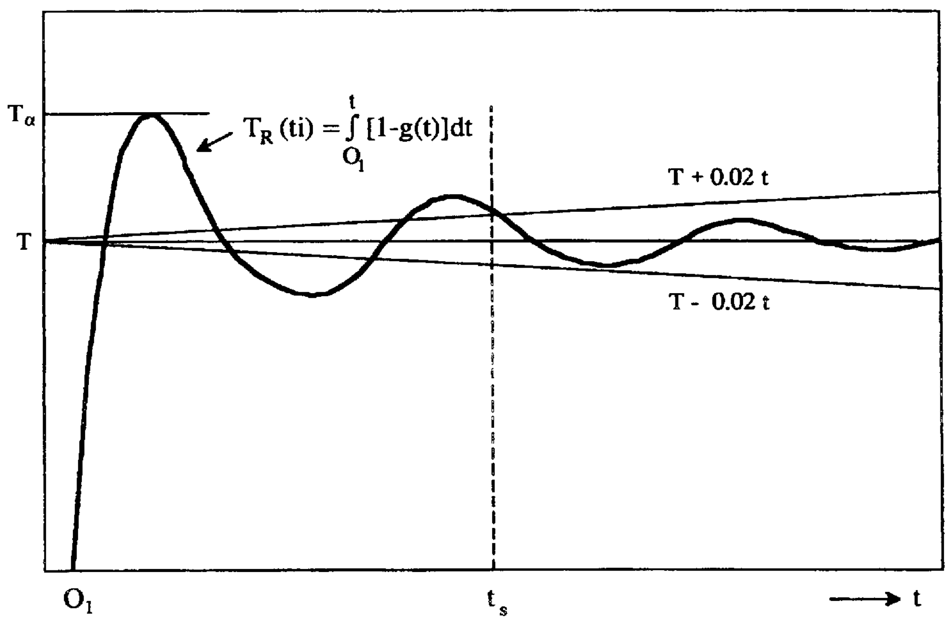


Figure 19—Definitions of response parameters with respect to $T(t)$

13.4.7 Estimation of system response using the convolution integral

An estimate of the response characteristics of the reference system can be obtained from the experimental step response and numerical impulse waveforms of the type to be measured in the tests. The output of the measurement system calculated from the convolution integral is then compared with the numerical input waveform to estimate the distortion of the waveform parameters introduced by the measurement system. This approach will provide an indication if the measurement system has an adequate response to meet the requirements of this standard. Since this approach requires numerical computation, it is best implemented using a computer and a digitized measurement of the experimental step response.

The output $V_O(t)$ is calculated from the experimental step response and the model input waveform $V_{in}(t)$ using the time derivative of Duhamel's integral:

$$V_O(t) = \int_0^t V_{in}(s)\,h(t-s)\,ds = \frac{d}{dt}\int_0^t V_{in}(s)\,g(t-s)\,ds \qquad (28)$$

where

$g(t-s)$ is the normalized experimental step response
$h(t-s)$ is the impulse response of the system

Since the impulse response is not directly measurable, the experimental step response is used. The system output can be found using either a direct numerical approximation to the integral of equation (28) or through numerical approximation of the frequency domain transformations of the waveforms. In the latter case, after multiplication, the frequency domain components shall be inversely transformed to obtain the estimate if $V_O(t)$ is used to estimate the system output. A useful model waveform for numerical input is that of the double exponential type for full lightning and switching impulses:

$$V_{in}(t) = V_O\,(e^{-\alpha t} - e^{-\beta t}) \qquad (29)$$

Values for and for standard lightning impulses are given in the following table:

Waveform	α (s^{-1})	β (s^{-1})
Standard 1.2 × 50	1.46×10^4	2.47×10^6
Standard 0.9 × 50	1.44×10^4	3.35×10^6

Chopped lightning impulse input waveforms can also be created from the double exponential models by piece-wise construction. The initial part of the waveform up to the chop can be numerically constructed using equation (29) while the part after the chop can be made of a linear decay to zero.

The experimental step response can be measured as described in 13.4.5. After normalizing the measured step response, equation (28) is applied using the numerical input waveform to calculate the output. The model input and calculated output waveforms are shown in figure 20. The output waveform parameters, such as voltage peak, front time, time-to-chop, etc., are defined in 8.1. These values can then be directly compared with waveform parameters of the numerical input waveform. If the differences in the voltage and time parameters exceed the requirements of section 12.7, then the system is inadequate and should not be used for the measurement of the types of impulses used in the calculations.

This technique should also not be used for correction of measured waveforms because systematic errors, random noise, disturbances, and other effects are not accounted for in the experimental step response measurement. Rather, the calculated output should be considered as an estimate of the best measurement of impulse waveforms of the type used for the calculations that can be made with that measurement system.

13.4.8 Evaluation of a measuring system by comparison method

The ability of a measuring system to measure a particular type of impulse may be determined by comparing the results obtained with those from an independent reference measuring system whose response characteristics have already been measured and found to comply with the requirements of this standard. 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 ensure that this does not occur.

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

13.4.8.1 Demonstration of linearity

If the measuring system under investigation is found to be suitable for measuring the amplitude and waveform of the test voltage when the comparison is made at low voltage, the linearity of the system under investigation up to the full test voltage shall be demonstrated by removing the reference system from the circuit and comparing the test voltage amplitudes against the impulse generator charging voltage at various levels up to the test voltage, or by using a field probe. In addition, there should be no perceptible change in waveshape when performing the linearity tests up to full voltage.

NOTE—The waveshape will possibly change when the reference measuring system is removed from the circuit. In this case, the circuit components should be adjusted to produce a waveshape as close as possible to that used during the comparison tests between the system under investigation and the reference measuring system.

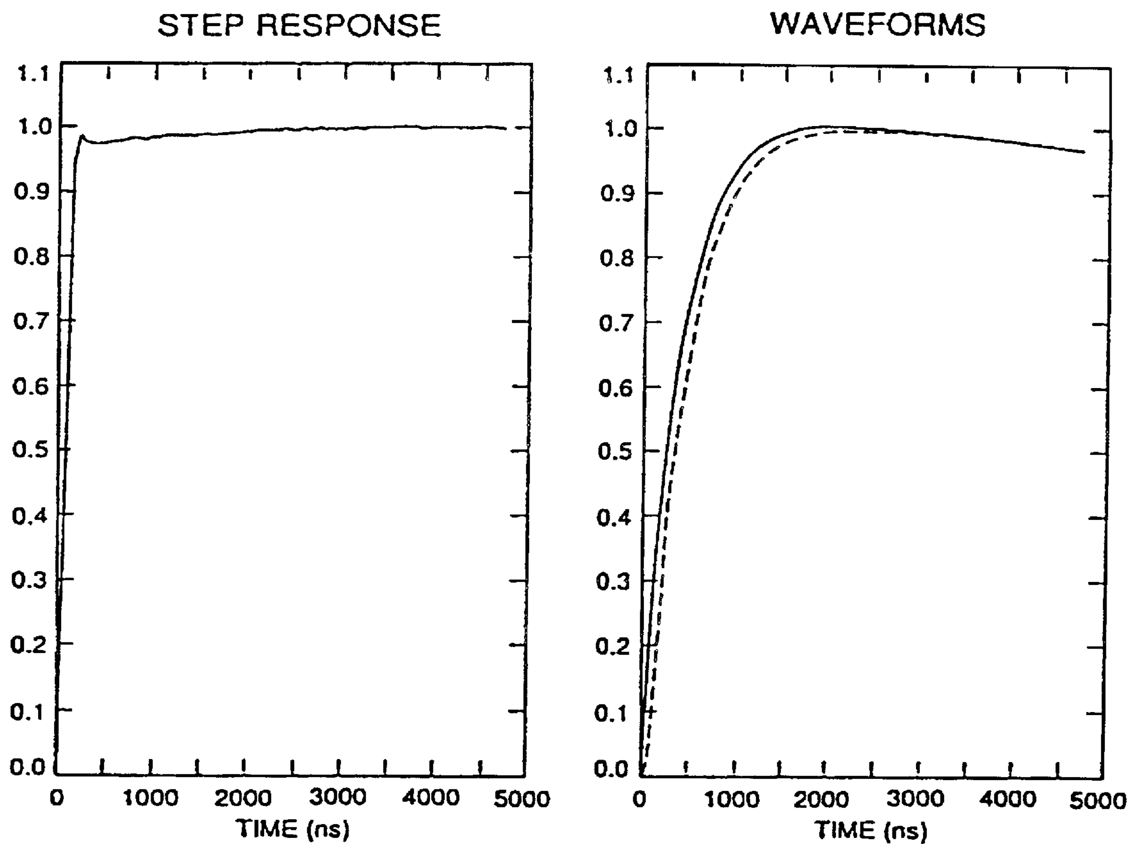
13.4.9 Various sources of errors and precautions

13.4.9.1 Divider ratio for long impulse duration

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 shall be

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



a) Measured normalized experimental step response

b) Input (solid line) waveform and calculated output (dashed line) waveform

Figure 20—Convolution method for system response

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.

13.4.9.2 Proximity effects

The performance of a divider may be affected by changes in stray capacitance. It is important that the determinations of accuracy and linearity be made with the apparatus in a typical working position.

13.4.9.3 Corona effects

For very high-voltage measuring systems, it may not be possible to eliminate corona on the high-voltage lead or other components. The measuring system may nevertheless be acceptable provided that the scale factor at a reduced voltage level and the scale factor at full voltage level comply with the requirements of this standard. In addition, there shall be no perceptible change in recorded waveshape between these two voltage levels.

13.5 Measurement of impulse currents

13.5.1 General

Measuring systems for impulse current have to 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.

13.5.2 Commonly used measuring systems

The following are typical systems used for measuring impulse currents:

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

13.5.2.1 Measuring system components

Many of the components of an impulse current measuring system are the same as those used in voltage measuring systems, and they should meet the same requirements as outlined in the appropriate parts of 13.4.2. 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 21. The resistance material should be nonmagnetic with a low temperature coefficient of resistance.
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.

The common grounding of the voltage and current metering is important in HV measurements. Any difference between the voltage and current reference grounds will be applied across the recorder input channels and can cause measurement errors (see 13.5.3).

13.5.2.2 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.

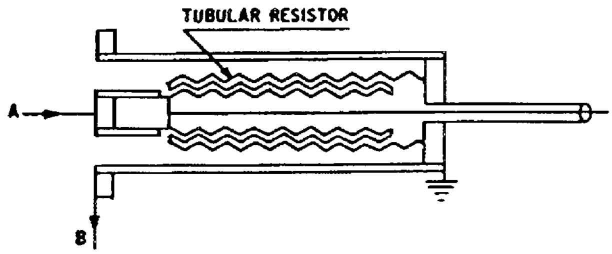
Tubular resistance shunts usually have an a periodic type of step response, and if the actual zero is used, the response time is given by

$$T = \left(\frac{\mu_o}{6}\right) \times \left(\frac{d^2}{\rho}\right) \tag{30}$$

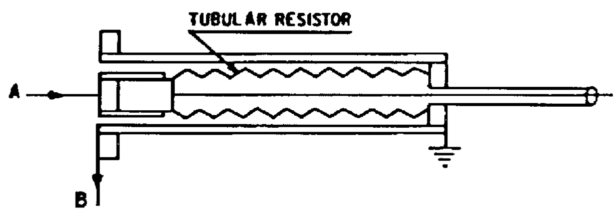
where

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

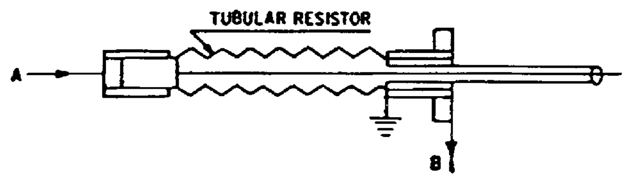
However, due to the use of virtual origin (O_1), the response time is determined more accurately from



a) Multiple tube, coaxial return



b) Coaxial return



c) Noncoaxial return

Figure 21—Tubular shunts for impulse current measurements (the impulse current flows from point A to point B)

$$T = \left(\frac{\mu_o}{8}\right) \times \left(\frac{d^2}{\rho}\right) \quad (31)$$

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 22.

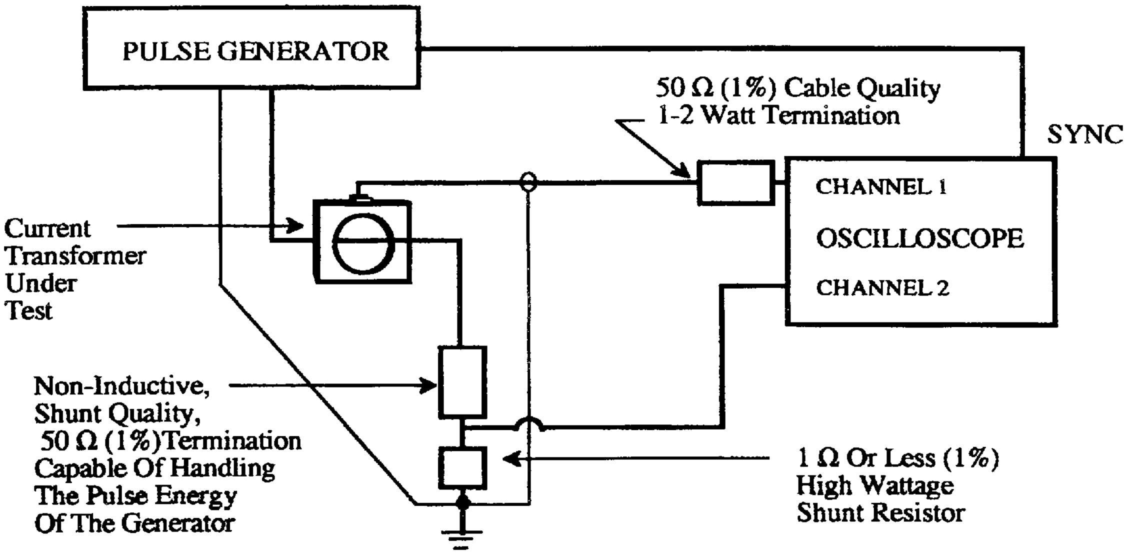


Figure 22—Circuit for checking the risetime rating of a current transformer

13.5.2.3 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 13.4.5 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 23. When the switch is closed, a current step with an 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 13.4.5), 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.

13.5.3 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

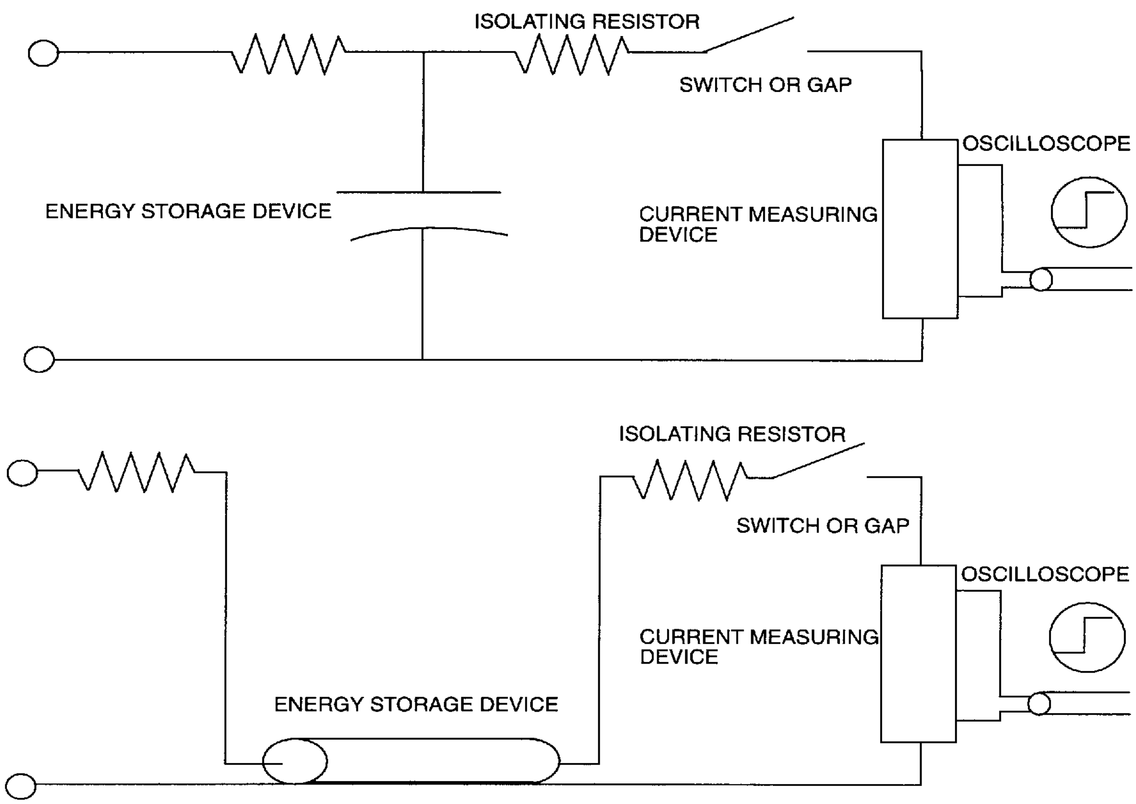


Figure 23—Impulse current step generator connections

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 transformers with magnetic cores is limited by core saturation. In order to avoid saturation, the max-

imum 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.

13.6 Evaluation of measurement accuracies

13.6.1 General

Any set of measurements is subject to errors, and the establishment of uniform standard techniques for measurement and testing requires that the accuracy of the measurement be controlled and known to within calculable limits. The absolute accuracy of any measurement can never be known due to the impossibility of determining the true value. Since this is the case, it is customary to estimate what the accuracy is by establishing limits on the measurement errors through direct testing and familiarity with the behavior of the measurement system. This subclause describes the different types of errors that occur in measurements and some of the methods for estimating the accuracy of measurements. Also included are some comments on their application to high-voltage measurements as defined by this standard.

13.6.2 Terms used in evaluation of accuracy

Error is the difference between the measured value of a quantity and the true value of that quantity under specified conditions.

NOTE—The absolute value of the error of a measurement cannot be known because it is impossible to determine the true value of the quantity to be measured. However, limits to the error can be set from measurements of the precision and estimates of the bounds to systematic errors.

The term "error" is occasionally used in technical literature for a known deviation from some accepted or nominal value, e.g., deviation from the nominal resistance value, or the transformer ratio value. In this subclause, the term "error" denotes only the unknown difference between the measured and true values.

Random errors are errors that have unknown magnitudes and directions and that vary with each measurement. They have statistical distributions associated with them, and their contributions to measurement accuracy can be analyzed using statistical techniques.

Systematic errors, or biases, are errors where the magnitudes and directions are constant throughout the calibration process. Their effects are estimated and may be reduced by the application of correction factors.

Accuracy refers to the degree of agreement between a measured value and the true value.

Precision refers to the discrepancy among individual measurements.

Uncertainty is an estimated limit based on an evaluation of the various sources of error.

13.6.3 Types of measurement errors

Errors that occur in a set of measurements consist of two components: random error and systematic error. The total error, ε, for a particular measurement of a quantity, χ_i, can be represented by the sum of the random (ε_r) and systematic (ε_s) errors:

$$\varepsilon = \chi_i - \tau = (\chi_i - \mu) + (\mu - \tau) = \varepsilon_r + \varepsilon_s \qquad (32)$$

where

χ_i is the result of a particular individual measurement
τ is the true value of the quantity to be measured
μ is the mean value of repeated measurements of the same quantity
ε_r is the random error in an individual measurement
ε_s is the systematic error in the measurement approach or system

In estimating the total uncertainty in a measurement, the two components of error can be treated separately.

These two types are illustrated in figure 24. In any measurement, both types of error occur, but one may dominate. The random error or precision of a set of measurements is characterized by a mean value, which is the limiting value of the average of an infinite number of measurements. The systematic error is the bias or offset in the measurements, which is the difference between the mean of the measurements, and the "true" value of the measurement.

An indication of the random error can be estimated by the computed standard deviation, s, if repeated identical measurements can be made. For a set of k measurements, an estimate of the standard error is found from the usual equation:

$$s^2 = \sum_{i=1}^{k} \left(\frac{(x_i - \bar{x}_k)^2}{(k-1)} \right) \quad (33)$$

where

$\bar{x}_k$ is the arithmetic mean of the k measurements

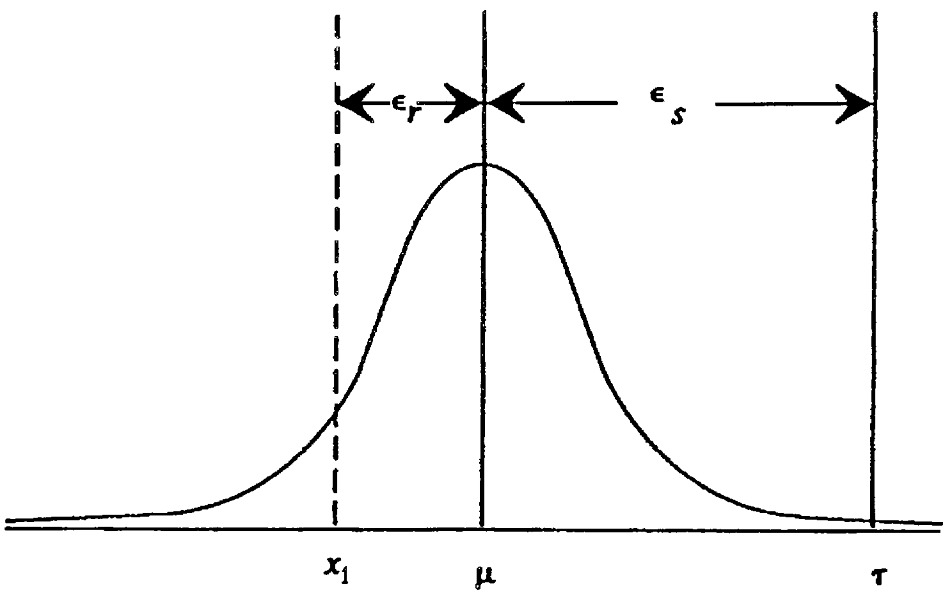


Figure 24—Measurement errors with parameters defined in equation (32)

The mean $\bar{x}_k$ for a set of k measurements is an estimate of μ,which is the limiting value of an infinite number of measurements.

This average does not differ from μ by more than Δ, where Δ is given by

$$\Delta = t \cdot \frac{s}{\sqrt{k+1}} \tag{34}$$

where

t is the value of Student's t obtained from table 2
k is the number of degrees of freedom

and the probability refers to the probability that the value μ of the quantity being measured lies within the interval $\bar{x}_k \pm \Delta$.

Table 2—Value of Student's *t*

Degrees of freedom	Probability			
	0.50	0.90	0.95	0.99
1	1.000	6.314	12.706	63.657
2	0.816	2.920	4.303	9.925
3	0.765	2.353	3.182	5.841
4	0.741	2.132	2.776	4.604
5	0.727	2.015	2.571	4.032
6	0.718	1.943	2.447	3.707
7	0.711	1.895	2.365	3.499
30	0.683	1.697	2.042	2.750
99	0.676	1.660	1.984	2.626
Infinite	0.674	1.645	1.960	2.576

The total systematic error can never be known because the true value of the quantity being measured is unknown. Rather, the limits on the systematic errors can be established based upon

a) Identification of sources of systematic errors that may occur in the measurement procedure
b) Past experience with the measurement system from the results of calibration
c) Some reasonable assumptions about the effect of environment on the measurement

Although this approach is somewhat subjective, it proves useful in practice. Each identified source of systematic error is characterized by the assumed shape of its probability distribution function and the estimated limits of the error (δ_i).

Figure 25 shows four different probability distribution functions and their standard deviations. The uniform distribution, which assumes that all values for the systematic error falling within the range set by the limits

$\pm\,\delta_i$ are equally probable, has a standard deviation given by $\delta_i/(\sqrt{3})$. It provides the most conservative estimate of the error (the maximum standard deviation) of the four distributions shown in the figure. If the systematic error is assumed to be normally distributed and limits of $\pm\,\delta_i$ define the 99% probability interval, the standard deviation is $\delta_i/3$, which provides the smallest estimate of the four distributions characterized by the same δ_i.

Once the sources of systematic error have been identified, it is useful to combine them with the estimate of the random error into a single statement of total uncertainty. Several methods for obtaining the total uncertainty are described below.

The simplest method is the initial expression in this discussion, $\varepsilon = (\varepsilon_r) + (\varepsilon_s)$. If the systematic errors are eliminated by calibration, only the random errors remain, and the uncertainty then becomes a multiple of s. It is frequently assumed that

$$\varepsilon_r = g\,s \tag{35}$$

where

g is the number of standard deviations (and is typically 1, 2, or 3 depending upon the desired reliability of the final estimate)
s is the experimental or computed standard deviation

Typical values of 1, 2, and 3 are used for the multiplying factors, depending on the experience of the metrologist. The use of these factors implies that the probability of making measurements that exceed the resulting uncertainties are 16%, 2.3%, and 0.13%, respectively.

Methods commonly used for estimating total uncertainty are described mathematically by the following formulas:

$$\varepsilon = g \cdot s + \sum_{i=1}^{k} \delta_i \qquad g = (1, 2, 3) \tag{36}$$

$$\varepsilon = g \cdot s + \left(\sum_{i=1}^{k} (\delta_i^2)\right)^{1/2} \qquad g = (1, 2, 3) \tag{37}$$

$$\varepsilon = \left((g \cdot s)^2 + \sum_{i=1}^{k} \delta_i^2\right)^{1/2} \qquad g = (1, 2, 3) \tag{38}$$

$$\varepsilon = K\left(s^2 + \frac{\sum_{i=1}^{k} \delta_i^2}{3}\right)^{1/2} \qquad K = 2, 3 \tag{39}$$

The first method, equation (36), gives the most conservative estimate of uncertainty by using a linear combination of the computed standard deviation for the measurements (the random error component) and the maximum limits of the component sources of systematic errors. This approach in all likelihood overestimates the measurement inaccuracy and should be considered a worst possible case, an estimate of the maximum possi-

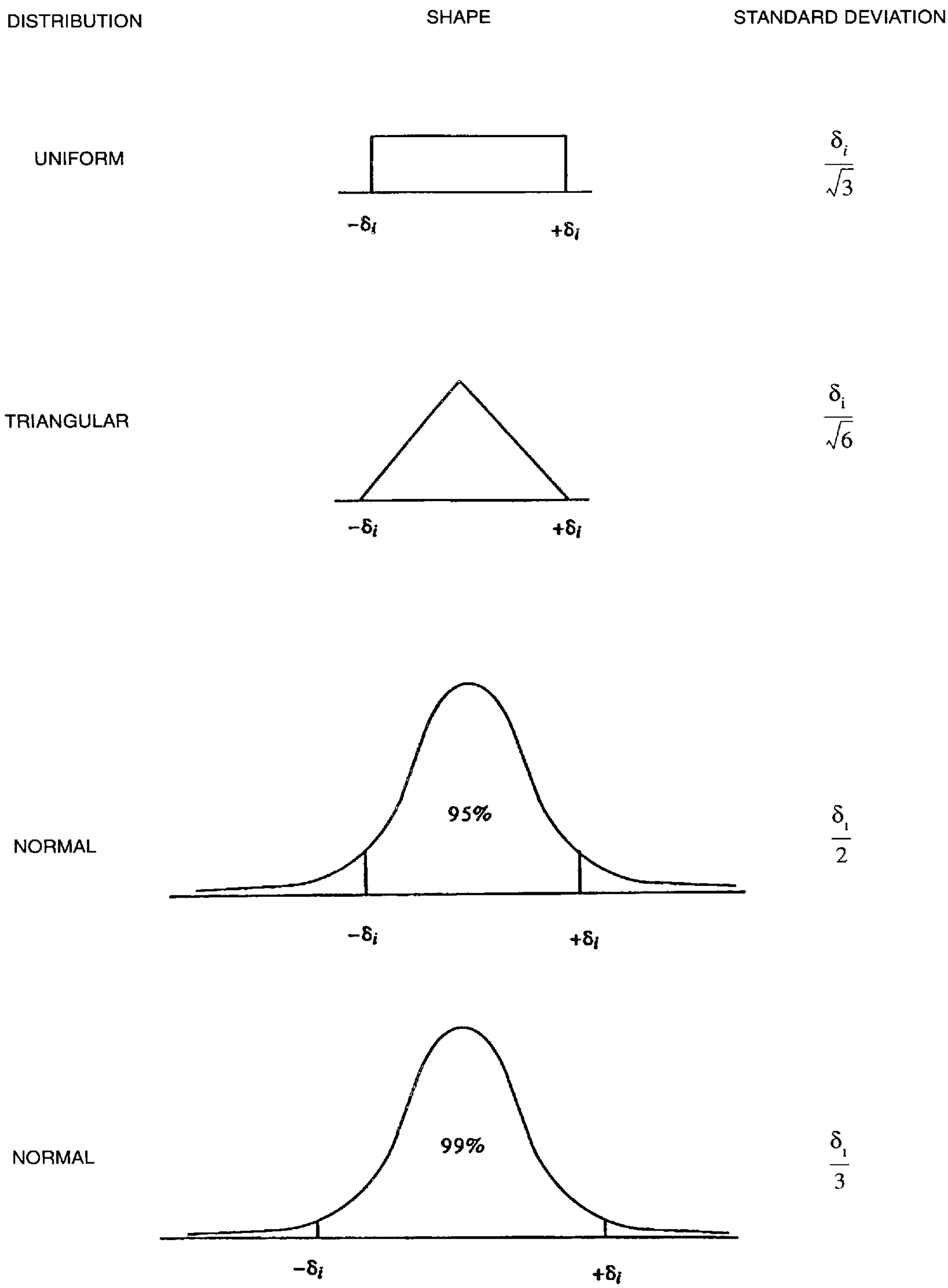


Figure 25—Examples of four different probability distributions and their standard deviations

ble limits of error. Equation (36) will result in an unrealistically large figure if the number of components of the systematic error is large.

The second and third methods, described by equations (37) and (38) respectively, combine the maximum limits of systematic error in quadrature and add this combination to the random error estimate either linearly, as in equation (37), or in quadrature, as in equation (38). Equation (38) is commonly referred to as the RSS (Root-Sum-of-Squares) method.

The fourth method, given by equation (39) and known as the PTB[4] approach, defines a total standard deviation that is given by a quadrature sum of the random error and the standard deviations of the individual systematic errors. The systematic errors are assumed to have uniform probability distributions as in case 1 of figure 25 with a standard deviation for each distribution of $\delta_i/(3)^{1/2}$. The PTB method [equation (39)] is not recommended for the case where one particular component of the total systematic error is much larger than the rest. For this special case, it is preferable to keep that component separate from the others and add it to the sum linearly. The methods based on equations (37), (38), and (39) imply that there is some independent cancellation of errors and are preferred when several independent component errors of similar magnitude are present.

These equations are useful in providing a single number to describe total measurement uncertainty and can determine whether a given system can make measurements within the allowable error limits prescribed by the standard. Proper application of the equations requires some guidance such as how to identify and estimate the various systematic errors for a particular configuration. Some remarks regarding this appear in the next subclause.

13.6.4 Examples of uncertainty limit evaluation

13.6.4.1 Measurement of impulse voltages

The limits to measurement errors prescribed by this standard for high-voltage impulse measurement systems are 3% or 5% (dependent on chopping time) in the measurement of the peak value of the impulse voltage, and 10% in the time parameters. This standard gives guidelines on how to ensure that an impulse measurement system will meet these requirements. It states that

a) The voltage divider ratio shall be stable and known with an error not exceeding 1%
b) The scale factor of the oscilloscope or peak voltmeter shall be stable and known with an error not exceeding 2%
c) The time scale of the oscilloscope shall be stable and known with an error not exceeding 2%

Application of equations (36) through (39), using assumed values of 1% and 2% for the systematic errors in divider ratio and oscilloscope scale factor, respectively, together with an assumed computed standard deviation of 1% for the standard deviation s of the random error and a multiplying factor $g = 2$, yields the results given in the table on page 71.

Equation (36) provides the greatest uncertainty (5%), while equation (38) provides the smallest (3%). Equation (36) tends to overestimate the error, but it does represent a quasi-absolute upper bound for the overall error. The PTB method [equation (39)] is slightly more conservative than the RSS method [equation (38)].

This example does not imply that the minimum error during impulse measurements cannot be reduced below 3%. Obviously, if the divider ratio and oscilloscope scale factor can be measured with greater accuracy, the overall accuracy of the measuring system may be improved. For example, if the systematic errors in ratio and scale factor are reduced to 0.5% and 1%, respectively, and s and g remain at 1% and 2%, the total uncertainty according to the RSS method becomes 2.29%.

[4]Physikalische-Technische Bundesanstalt.

Uncertainty calculation method	ε (%)
Equation (36)	5.00
Equation (37)	4.23
Equation (38)	3.00
Equation (39)	3.27

13.6.4.2 Measurement of alternating voltage

A commonly used technique to measure the peak value of an alternating voltage is to measure the rectified mean current flowing through a capacitor that is connected to the points between which the voltage is to be measured.

The peak value of the voltage to be measured is given by

$$V_p = \frac{I_r}{4Cf} \tag{40}$$

where

V_p is the voltage (in volts)

I_r is the current (in amperes)

C is the capacitance (in farads)

f is the frequency (in hertz)

Assuming systematic error of 0.1% in the values of capacitance and frequency and 0.5% standard deviation in the current measurement (random error) together with a multiplying factor $g = 2$, equations (36) through (39) yield the results given in the following table.

Uncertainty calculation method	ε (%)
Equation (36)	1.20
Equation (37)	1.14
Equation (38)	1.01
Equation (39)	1.01

In this example, the random error predominates and, therefore, all four equations yield approximately the same result. A similar result would occur if a systematic error were to predominate.

14. Tests in different ambient conditions

14.1 Dry tests

The test object shall be dry and clean. If not otherwise specified by the appropriate apparatus standard, the test should be made at ambient temperature, and the procedure for voltage application should be as specified in clauses 5, 6, 7, and 8.

14.2 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 3.

Three precipitation rates and two resistivities are found in table 3. They appear under the headings "Standard test procedure," "Conventional procedure—European practice," and "Conventional procedure—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 14.2.3.

Table 3—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 (Ω·m)	
Standard test procedure	1.0–2.0	1.0–2.0	±0.5 from average	Ambient ± 15	100 ± 15	60
Conventional procedure—European practice	3 ± 0.3	–	3 ± 0.75	Ambient ± 15	100 ± 10	60
Conventional procedure—practice in USA	5 ± 0.5	–	5 ± 1.25	Ambient ± 15	178 ± 27	10

14.2.1 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.

14.2.2 Standard wet test

The precipitation conditions in table 3 under "Standard test procedure" are recommended for tests with all types of test voltages, and on all types of apparatus designed for outdoor use.

14.2.3 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 100–750 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.

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 3. Pressure and distance can be varied to achieve the required conditions. Any type and arrangement of nozzles meeting the requirements given in table 3 may be used. An example of a nozzle that has been found satisfactory in practice is shown in figure 26, and typical performance data are given in the note after figure 26. Greater spray distances may be obtained if the nozzles are directed upward at an angle of 15–25° from horizontal. Note that if the water pressure is increased above the recommended limits, the water jets may break up prematurely and cause an unsatisfactory spray at the test object.

The test object should be pre-wetted for at least 15 min. The pre-wetting may be done using unconditioned water. Conditioned water shall meet the requirements of table 3. 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 3 shall remain within the specified tolerances throughout the remainder of the test.

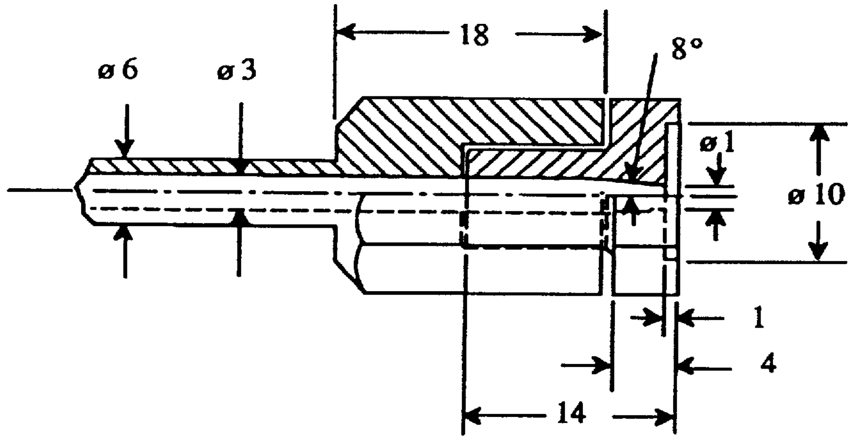
Unless otherwise specified by the appropriate apparatus standard, the test procedure for wet tests should be the same as that specified for the corresponding dry tests. In general, for all alternating and direct voltage wet withstand tests, it is recommended that one flashover should be permitted provided 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 $3 \times 10^5 - 4 \times 10^5$ Pa (3–4 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 26 are 9–11 m.

15. Artificial contamination tests

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 particular service environment. The effects of washing on insulators in service by natural rain is to 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 appropriate apparatus standards to introduce variations or to give more specific requirements for particular



NOTE—Details of orifice only; all dimentions given in millimeters.

Figure 26—Nozzle

classes of apparatus. It should be noted that all contamination tests in this standard apply only to ceramic (porcelain and glass) insulators. Although nonceramic insulators are currently being tested for contamination performance, no standardized procedures have been agreed upon.

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 supply are given in 15.3 and 15.4 for tests with alternating voltage and direct voltage, respectively.

15.1 Preparation of 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 ensure that corrosion products will not contaminate 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. 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.

Unless otherwise specified by the appropriate apparatus standard, the test object, with its metal fittings that are integral parts of it, shall be mounted in the test chamber in its in-service orientation. The minimum clearances between any part of the insulator and any grounded object, other than the structure that supports the insulator and the spray 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.

15.2 General test procedures

15.2.1 Introduction

Contamination tests fall into two categories:

a) The clean fog test, which is described in 15.5
b) The salt fog test, which is described in 15.6

Artificial contamination tests involve 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

15.2.2 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 withstands, 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.

15.2.3 Determination of the maximum withstand voltage at a given degree of contamination

A series of tests shall be carried out on insulators having a given degree of contamination. Each test shall be carried out at any one of a number of voltage levels, each of which shall be about 1.05 times the next lower value. The tests can be carried out in any sequence provided that

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

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

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

The insulator shall be subjected to at least ten "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. The voltage step shall be approximately 5% of the expected 50% withstand voltage.

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 following 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 equation (41).

$$V_{50} = \frac{(\sum (n_i V_i))}{N} \tag{41}$$

where

V_i is an 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 19) can be used to obtain V_{50}.

15.3 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 voltage (phase-to-ground) the insulator is required to withstand under normal operating conditions. It is higher than this value for phase-to-phase configurations or for isolated neutral systems.

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 in equations (42) and (43).

$$I_{sc} \geq 6 \qquad \text{for } L_s < 27 \tag{42}$$

$$I_{sc} \geq L_s - 10 \qquad \text{for } 27 \leq L_s < 42 \tag{43}$$

where

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

L_s is the specific creepage distance [in mm/(kV × $\sqrt{3}$)]

The definition of specific creepage distance in equations (42) and (43), namely actual creepage distance divided by the product of line-to-ground voltage and the square root of three, is consistent with terminology in IEC standards.

The requirements for the short-circuit current are given graphically in figure 27.

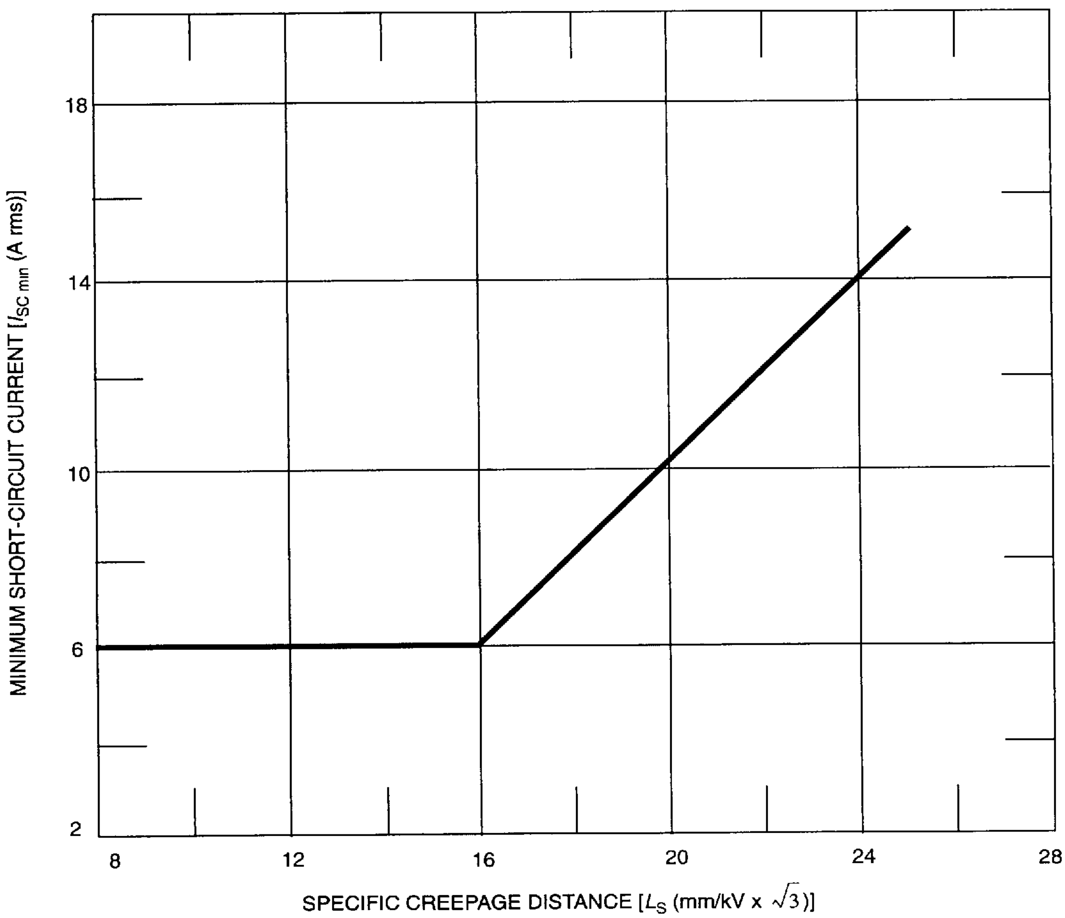


Figure 27—Minimum short-circuit current versus specific creepage distance for artificial contamination tests (kilovolts equals line-to-ground voltage)

The other requirements on the supply are

a) The resistance/reactance ratio (R/X) shall be equal to or greater than 0.1

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

When the value of I_{sc} of the power supply, although higher than 6 A, does not comply with the limits given in equations (42) and (43), 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 equation (44).

$$I_{SC}/I_{h\ max} \geq 11 \qquad (44)$$

where

I_{sc} is the short-circuit current [in amperes (rms)]
$I_{h\,max}$ is the highest leakage current pulse amplitude [in amperes (peak value)]

15.4 Power supply requirements for direct-voltage artificial contamination tests

The ripple factor of the test voltage, demonstrated in a suitable way, shall be less than 3% for a current of 100 mA with a resistive load.

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

Criteria for demonstration that relative voltage drops greater than 10% are acceptable are under consideration. Provisionally, relative voltage drops exceeding 10%, but no higher than 15%, may be tolerated, provided that the mean of the relative voltage drops, evaluated during the whole relevant current pulse, does not exceed 5%.

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

If a flashover occurs during the time a relative voltage overshoot is between 5% and 10%, the test is not valid.

15.5 The clean fog test

15.5.1 Introduction

The clean fog test may be performed either with alternating voltage or direct voltage (see [B62] and [B72]).

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.

There are two alternative procedures in this method: the insulator is subjected to the test voltage after the layer has dried, or the insulator is subjected to the test voltage while still wet.

In both alternatives, the fog generation is started immediately after the test voltage is applied. The clean 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 spray 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 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.

15.5.2 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.

15.5.3 Contaminant

The contaminant consists of a suspension that shall be prepared using the composition given in 15.5.3.1.

15.5.3.1 Kaolin composition

The kaolin composition consists of

a) 40 g kaolin
b) 1000 g tap water
c) A suitable amount of NaCl, of commercial purity

NOTE—Tonoko or any other inert material may be an alternative to kaolin as the inert material. In this case, it shall be noted that these materials may give considerably different test results from kaolin. This has to be taken into account when comparing the results or when specifying test voltages and test severities. The amount of nonsoluble material on the insulator surface affects the test results. This matter is under consideration.

When the volume conductivity of the water is higher than 0.05 S/m, the use of demineralized 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 tentative contaminations. The desired volume conductivity is reached by adjusting the amount of salt in the slurry. As a rough guide, table 4 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 4.

Table 4—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

15.5.3.2 Main characteristics of the inert materials

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 5.

Table 5—Main characteristics of the inert material used in clean fog tests

Type of inert material	Weight composition (%)				Granulometry (cumulative distribution) (μm)			σ_{20} (μS/cm)
	S_iO_2	Al_2O_3	Fe_2O_3	H_2O	16%	50%	84%	
Kaolin	40–50	30–40	0.3–2.0	7–14	0.1–0.2	0.4–1.0	2–10	15–200

NOTES

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

2—Volume conductivity for the characterization of inert material is determined with the use of demineralized water.

15.5.4 Application of the contamination layer

The slurry described in 15.5.3.1 shall be applied by spraying it or flowing it onto the dry insulator previously cleaned according to 15.5.2, 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 spray 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 desirable 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.

The practice of flooding the prepared slurry over the insulator surface ("flow-on" technique) is particularly suitable for large or long insulators.

A preconditioning process, as specified for the salt fog test, is not necessary with the solid layer methods. More details are given below.

The layer shall be left to dry prior to submission of the insulator to the test. More details are given in the following subclauses.

15.5.5 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.

15.5.5.1 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 where only one cylindrical insulator is available for 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 demineralized water. The resulting slurry is kept stirred for at least 2 min 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:

$$\sigma_{20} = \sigma_\Theta [1 - b(\Theta - 20)] \quad (45)$$

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 °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 5–30 °C, the factor b can be obtained by interpolation.

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 0.004–0.4 S/m):

$$S_a = (5.7\sigma_{20})^{1.03} \quad (46)$$

The salt deposit density, S_{dd} (in mg/cm^2), is then obtained by the following formula:

$$S_{dd} = \frac{S_a V}{A} \quad (47)$$

where

V is the volume of the slurry (in cm^3)
A is the area of the cleaned surface (in cm^2)

15.5.5.2 Layer conductivity (*K*)

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

$$F = \int_0^L [1/p(l)]\, dl \qquad (48)$$

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 to the insulator a voltage not lower than 700 V rms/m 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 (38).

15.5.6 General requirements for wetting of the layer

The test object shall be wetted by means of fog generators, which provide a uniform fog distribution over the whole 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.

15.5.7 Additional recommendations for clean fog tests

The additional recommendations given in the following subclauses go more deeply into the practices of the clean fog 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 inaccuracies.

15.5.7.1 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 15.5.2. 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.

15.5.7.2 Drying of the pollution layer

Natural drying of the pollution layer on the insulator may be sufficient, provided that it lasts long enough (6–8 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 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.

15.5.7.3 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 28 contaminated at the S_{dd} value equal to 0.07 mg/cm^2, shall be put unenergized 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 15.5.5.2. The increase of the layer conductance in time shall be monitored and compared with the reference curve given in figure 28. If necessary, a readjustment of the fog steady rate shall be carried out to ensure that the measured curve matches the reference one.

15.5.7.4 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 wipings of that area shall be performed. As a guide, 2–4 L of demineralized 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.

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 whole area of the insulator is in the interval 0.7–1.3.

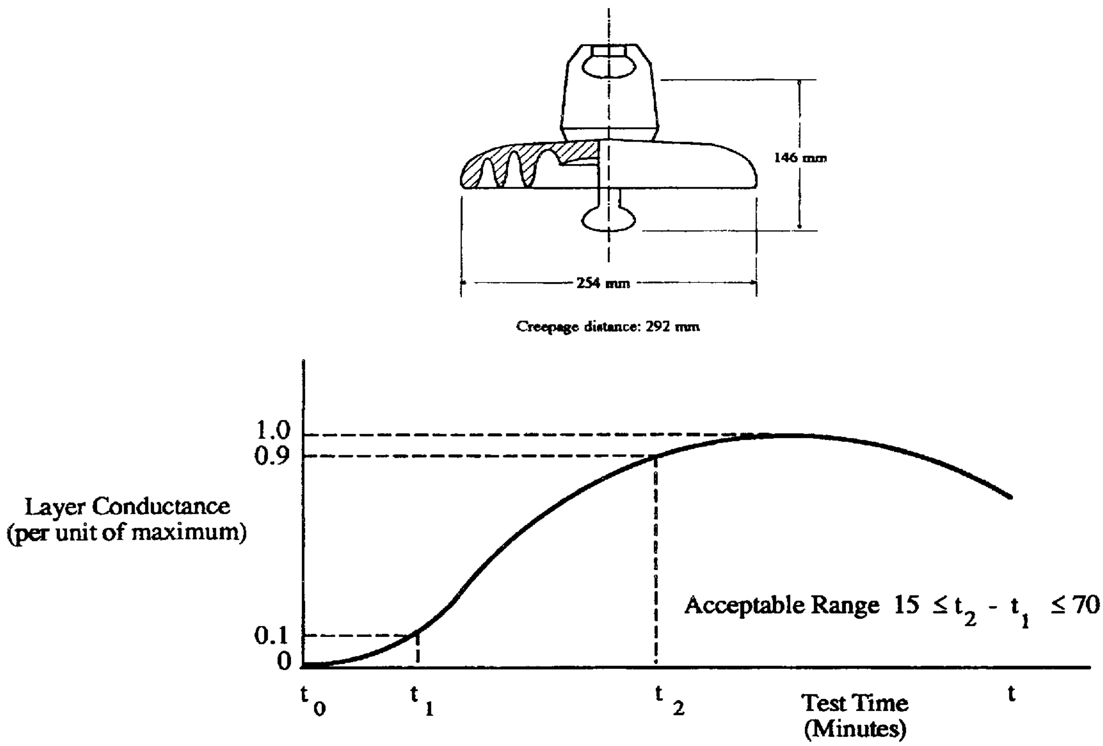


Figure 28—Control of wetting action of the steam fog: layer conductance recording during the test on the chosen dummy insulator

15.5.8 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.

15.5.8.1 Procedure 1—wetting after energization

For this procedure, the insulator is contaminated using kaolin composition (see 15.5.3.1). The degree of contamination is generally expressed in terms of salt deposit density (see 15.5.5.1).

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, unenergized 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 15.5.2 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 generators shall be under the test object as close as possible to the floor level. In all cases they shall be at least 1 m 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 28 and 15.5.7.3.

The test voltage is maintained until flashover occurs. Otherwise it is maintained for 100 min 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.

15.5.8.2 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 may be used also. The insulator is prepared for the test according to 15.5.2 and placed in its test position in the chamber, after which the fog generation is started.

Steam fog is preferably used. A steam fog generator, consisting of a distribution pipe with nozzles spaced at equal distance is shown in figure 29, as an example.

Instead of the steam fog, it is permitted to use a fog generated with nozzles spraying warm or cold water (see as an example the device in figure 30), 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.

For the evaluation of the layer conductivity, layer conductance measurements are performed on the tested insulator according to 15.5.5.2.

The flow rate of the fog input in the chamber, at normal ambient temperature, shall be sufficiently high so that the layer conductivity reaches its maximum value within 20–40 min 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 in a time not exceeding 5 s. The voltage is maintained until flashover, or for 15 min if no flashover occurs.

The insulator is then removed from the fog chamber and allowed to dry. It is placed for the second time in the chamber 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 min if no flashover occurs. No more than two tests can be performed on an insulator with the same contamination layer.

15.5.8.3 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 15.5.8.1 for Procedure 1 or 15.5.8.2 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.

15.6 The salt fog test

15.6.1 Introduction

The salt fog test may be performed with alternating voltage (see [B62]), but at present it is not suitable for standardization when used with direct voltage (see [B72]).

1. Low-pressure boiler, capacity about 20 L
2. Electric heater, 12 heating coils, each 3 kW
3. Feed-water regulator valve
4. Pressure-equalizing pipe
5. Boiler feed pump: 50 L/h,1 bar
6. Connection for softened water
7. Connection for compressed air
8. Adjustable compressed-air reduction valve
9. Pressure gauge: 0–5 bars
10. Compressed air valve, electric remote controlled
11. Injector nozzle: 7.5/16 mm diameter
12. Multipart nozzle pipe. 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
13. Nozzle, internal diameter: 1.6 mm; distance between adjacent nozzles: 30 mm
14. Plastic tent
15. Test object

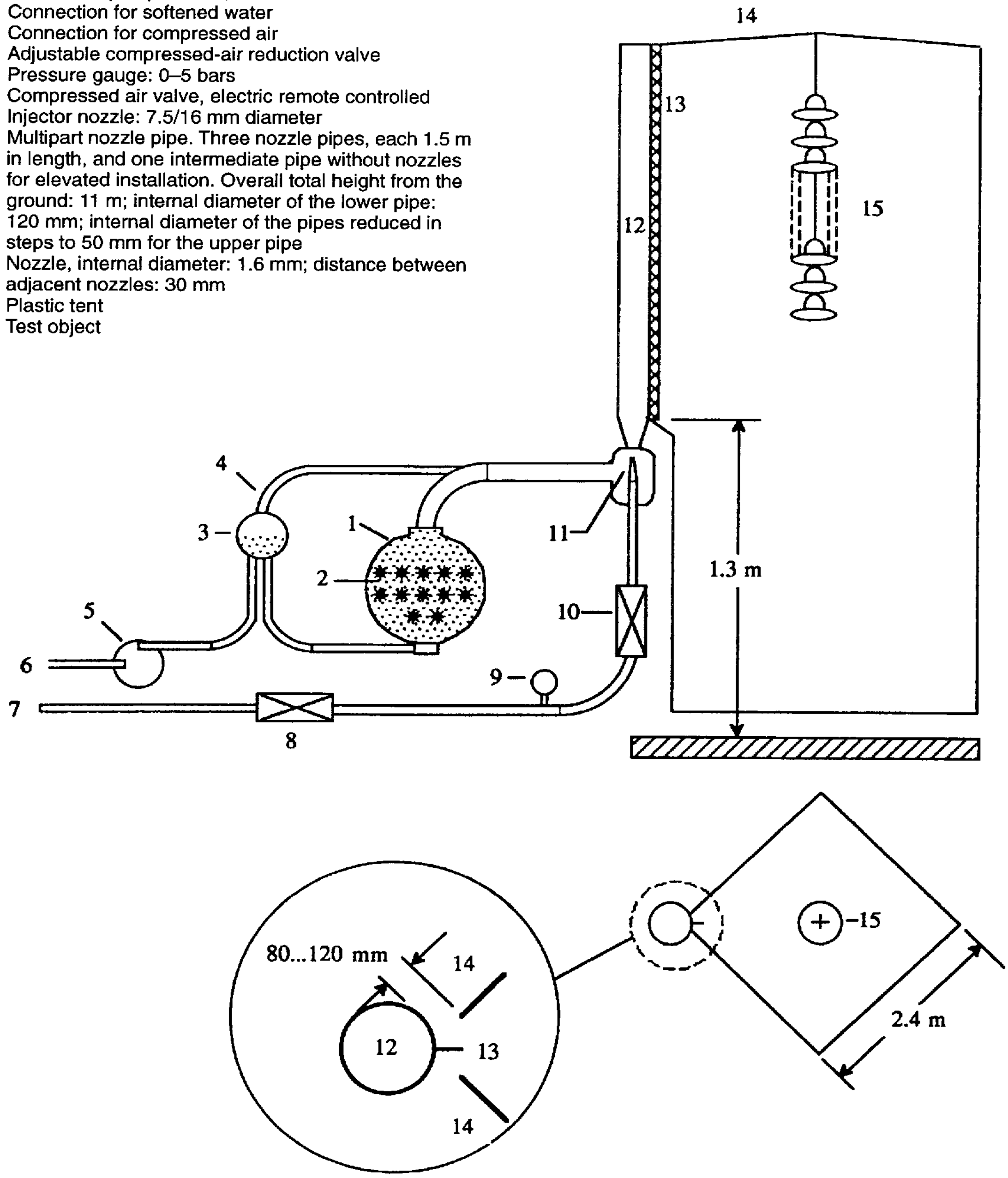


Figure 29—Typical arrangement of the steam-fog generator

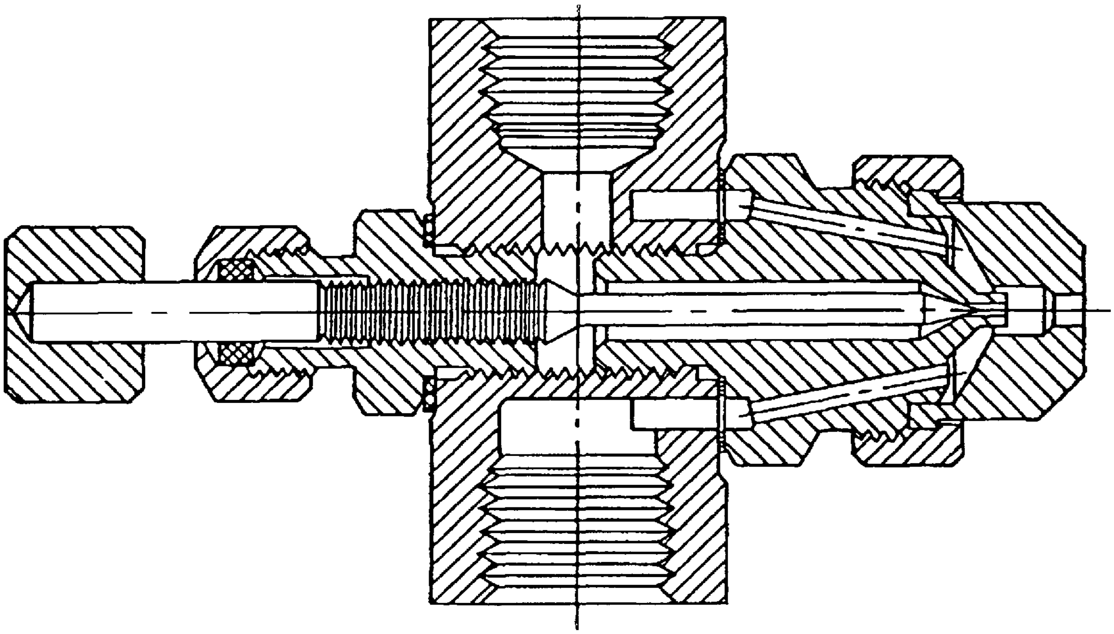


Figure 30—Example of fog nozzle—concentric air and liquid orifices

The insulator is subjected to a salt spray that provides an ambient contamination defined by a specified salinity (in kilograms per meter cubed) 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 nor 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.

15.6.2 Insulator preparation

The insulator shall be cleaned by washing it with water, preferably at about 50 °C, to which a neutral detergent such as trisodium phosphate (Na_3PO_3) has been added, and then thoroughly rinsing the insulator with clean water.

15.6.3 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 deionized 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*, revised by Gessner G. Hawley (included in Encyclopedia of Chemistry. New York: Van Nostrand Reinhold Co., 1971).

The salinity to be used shall be one of the values: 2.5 kg/m^3, 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, and 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 6. 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 (46).

The density correction shall be made using the following formula (valid only for salinities greater than 20 kg/m^3):

$$\delta_{20} = \delta_{\Theta}[1 + (200 + 1.3S_a)(\Theta - 20) \times 10^{-6}] \quad (49)$$

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 6—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	–
1	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

Table 6—Salt-fog method: correspondence between the value of salinity, volume conductivity, and density of the solution at a temperature of 20 °C *(continued)*

Salinity S_a (kg/m^3)	Volume Conductivity σ_{20}(S/m)	Density δ_{20} (kg/m^3)
112	13	1074.6
160	17	1104.5
224	20	1140.0

15.6.4 Spraying system

The fog is produced in the test chamber by means of the specified number of sprays 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 nozzle 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.

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 spray nozzle is shown in figure 31.

The sprays 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 32, 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.

The sprays shall be spaced at 0.6 m intervals, each spray 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 sprays. This alignment can be checked for vertical sprays by lowering the solution nozzle, passing water through the air nozzle and directing it towards the opposing spray and, afterwards, raising the solution nozzle to the operating position. The midpoint of the insulator shall be preferably in line with the mid-points of the columns of sprays. Both columns shall extend beyond the insulator at both ends by at least 0.6 m.

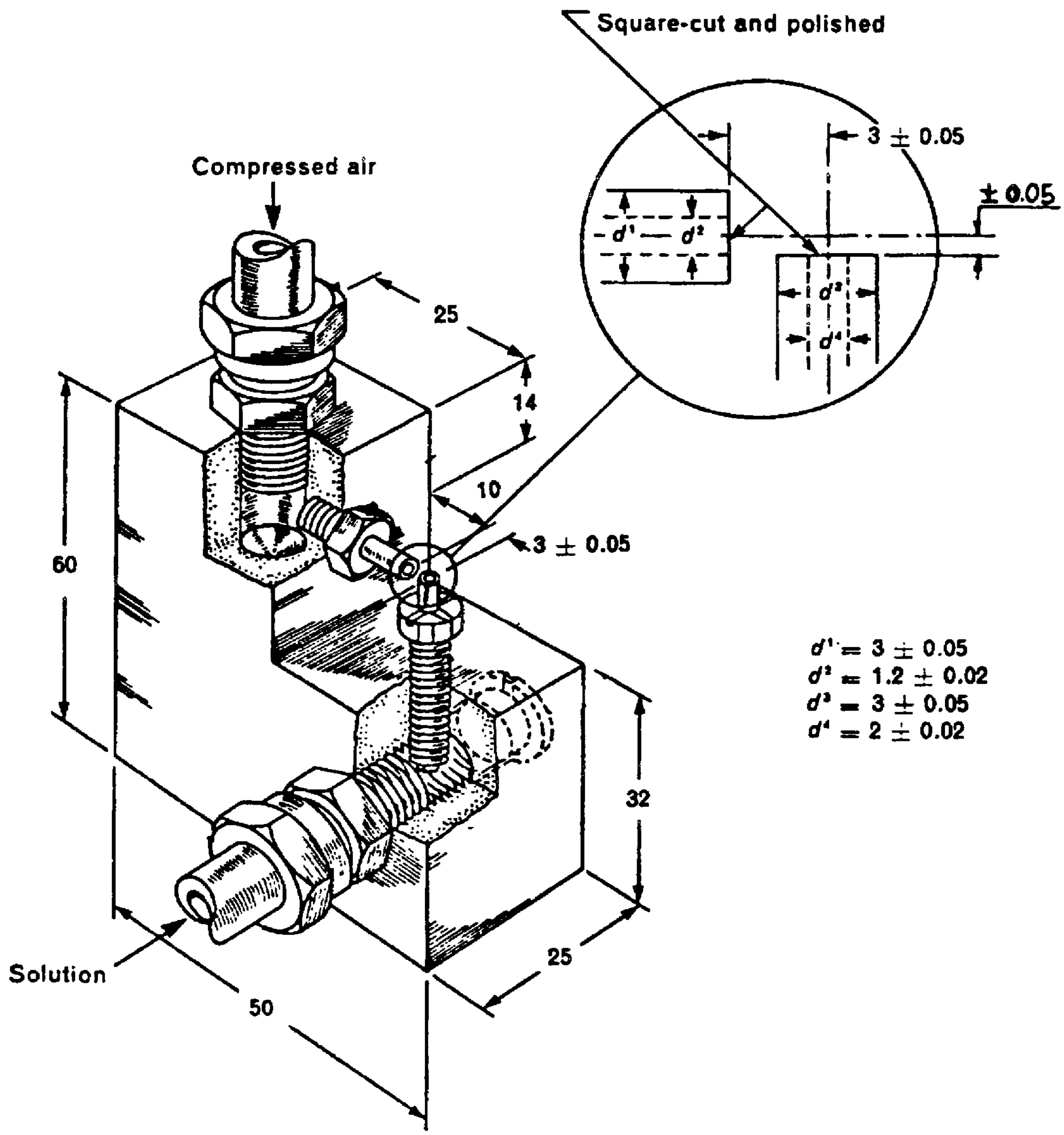
The minimum number of sprays per column shall be

$$N = (H/0.6) + 3 \tag{50}$$

where

N is the number of sprays per column
H is the length of the insulator (in m)

The sprays 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 spray shall be 0.5 cm^3/min ± 0.05 cm^3/min for the period of the test, and the tolerance on the total flow to all sprays shall be ±5% of the nominal value.



NOTE—All dimensions in millimeters.

Figure 31—Nozzle used for the salt fog test

15.6.5 Conditions before starting the test

The test shall start while the insulator, cleaned according to 15.6.2, 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 nor 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.

15.6.6 Preconditioning process

The insulator, prepared in the normal way, is subjected to the test voltage at the reference salinity for 20 min or until the insulator flashes over; if the insulator does not flash over, the voltage is raised in steps or 10% of the test voltage every 5 min until flashover.

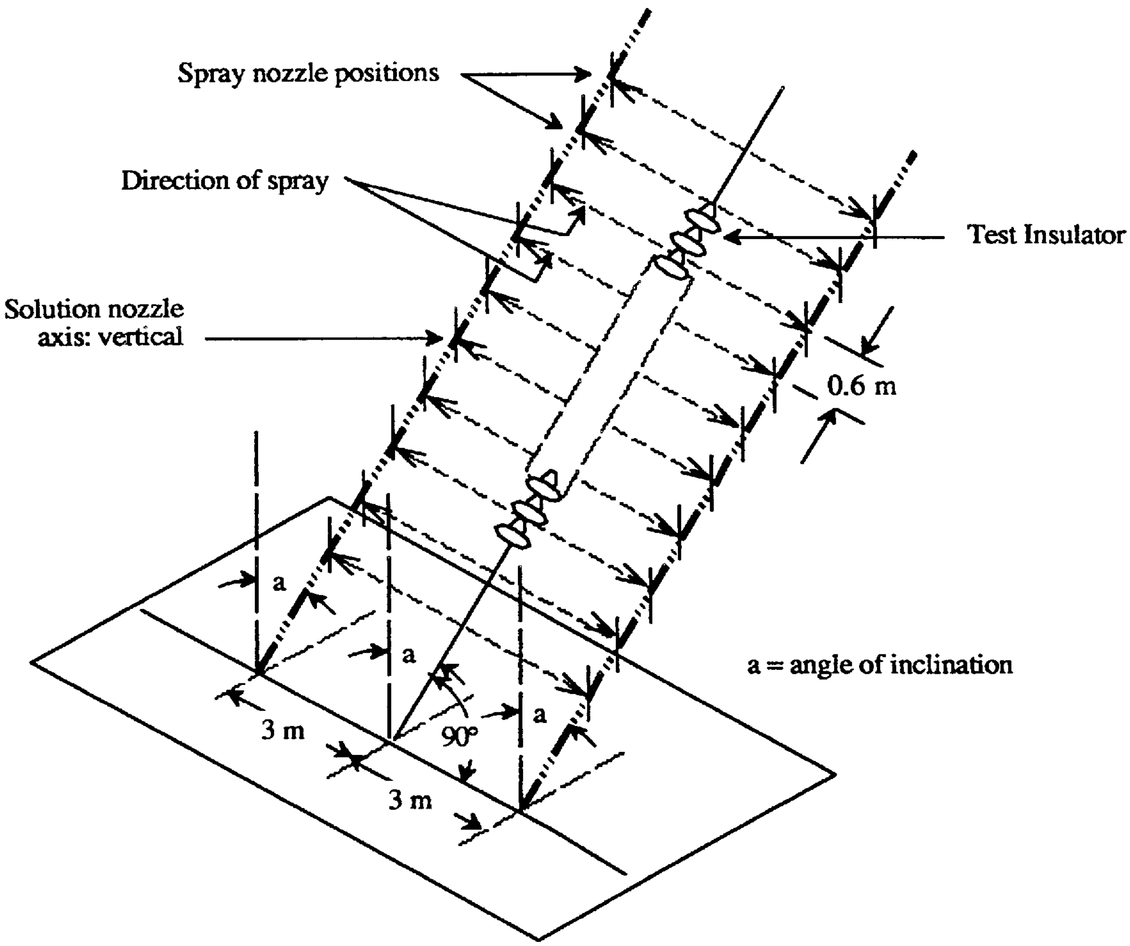


Figure 32—Test layout for inclined insulators

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 min until flashover. The last process is repeated six further 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 min until flashover. After eight flashovers, the fog shall be cleared, the insulator shall be washed with tap water, and then the withstand test (see 15.6.7.1) shall start as soon as possible afterwards.

The characteristics of the voltage source in the preconditioning process are to be not lower than the reference ones in the withstand test (see 15.3 and 15.4).

If the preconditioning process performed at the reference salinity would require excessively high voltages, the use of higher values of salinity is permitted for the preconditioning. Also, if with this expedient the voltage required is too 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.

15.6.7 Test procedure

15.6.7.1 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 15.6.5 and after the preconditioning of the insulator according to 15.6.6.

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 15.6.3. The duration of each test shall be 1 h if no flashover occurs before that time has elapsed. The insulator shall be carefully washed with tap water before each subsequent test.

15.6.7.1.1 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 15.6.7.1. 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 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.

16. Atmospheric correction

16.1 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

$$b = 0.1333H \qquad (51)$$

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.

16.2 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.

The disruptive discharge voltage is proportional to the atmospheric correction factor, K, defined by equation (52).

$$k = k_1 k_2 \tag{52}$$

where

k_1 is the air density correction factor given in 16.2.1
k_2 is the humidity correction factor given in 16.2.2

If not otherwise specified by the appropriate apparatus standard, the voltage, V, to be applied during a test on external insulation is determined by

$$V = V_0 K \tag{53}$$

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:

$$V_0 = V/K \tag{54}$$

The test report shall always contain the actual atmospheric conditions during the test and the correction factors applied.

16.2.1 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

$$k_1 = \delta^m \tag{55}$$

where

m is an exponent defined in 16.2.3

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

$$\delta = \left(\frac{b}{b_0}\right)\left(\frac{273 + t_0}{273 + t}\right) \quad (56)$$

16.2.2 Humidity correction factor (k_2)

The humidity correction factor may be expressed as

$$k_2 = k^w \quad (57)$$

where

- k is a parameter that depends on the type of test voltage and that, for practical purposes, may be approximately obtained as a function of the ratio of absolute humidity, h, to the relative air density, δ, using the curves of figure 33
- w is an exponent defined in 16.2.3

For values of h/δ in excess of 15 g/m^3, humidity corrections are still under consideration, and the curves of figure 33 may be regarded as upper limits.

16.2.3 Exponents *m* and *w*

Since the correction factors depend on the type of predischarges, this fact can be taken into account by considering the parameter g defined in equation (58).

$$g = \frac{V_B}{500 L \delta k} \quad (58)$$

where

- V_B is the (measured or estimated) 50% disruptive discharge voltage at the actual atmospheric conditions (in kV). In the case of a withstand test where an estimate of the 50% disruptive discharge voltage is not available, V_B can be assumed at 1.1 times the test voltage.
- L is the minimum discharge path (in meters)

The exponents m and w are still under consideration. Approximate values are given in figure 34.

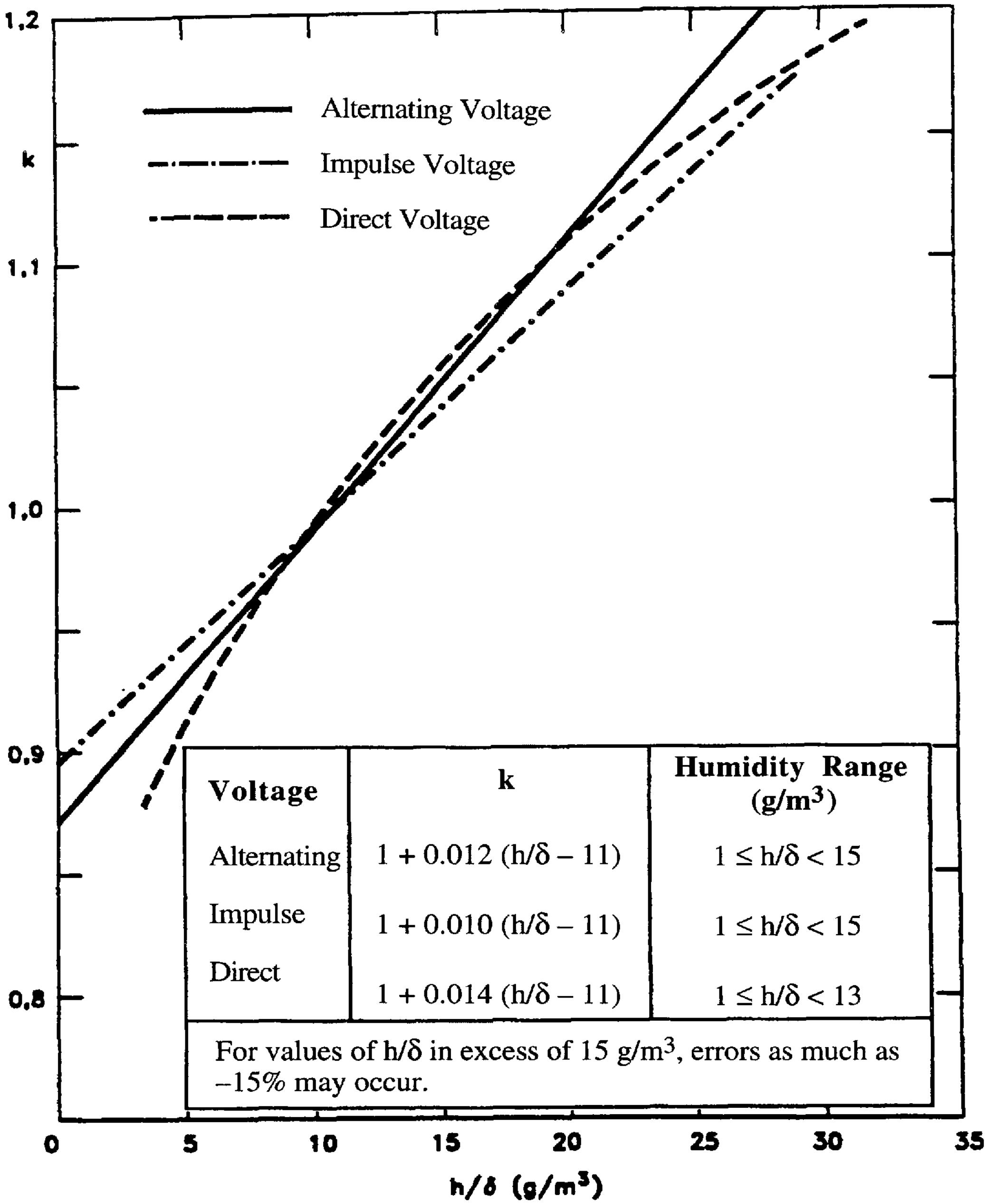
NOTE—The values of exponents m and w have been deduced from experimental values obtained in different conditions. These are, however, limited to altitudes between sea level and 2000 m.

16.2.4 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.

16.3 Measurement of humidity

The measurement of humidity is usually made by means of a hygrometer consisting of two ventilated accurate thermometers, one being dry, the other wetted. The absolute humidity as a function of the two thermometer readings is determined by figure 35, which also permits a determination of the relative humidity. It is



Voltage	k	Humidity Range (g/m³)
Alternating	1 + 0.012 (h/δ – 11)	1 ≤ h/δ < 15
Impulse	1 + 0.010 (h/δ – 11)	1 ≤ h/δ < 15
Direct	1 + 0.014 (h/δ – 11)	1 ≤ h/δ < 13
For values of h/δ in excess of 15 g/m³, errors as much as –15% may occur.		

Figure 33—Parameter *k* as a function of h/δ

important to provide adequate air flow (4–10 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.

16.4 Conflicting requirements for testing internal and external insulation

While withstand levels are specified under standard atmospheric conditions, cases will arise where the application of atmospheric corrections (due to laboratory altitude or to extreme climatic conditions) results in the

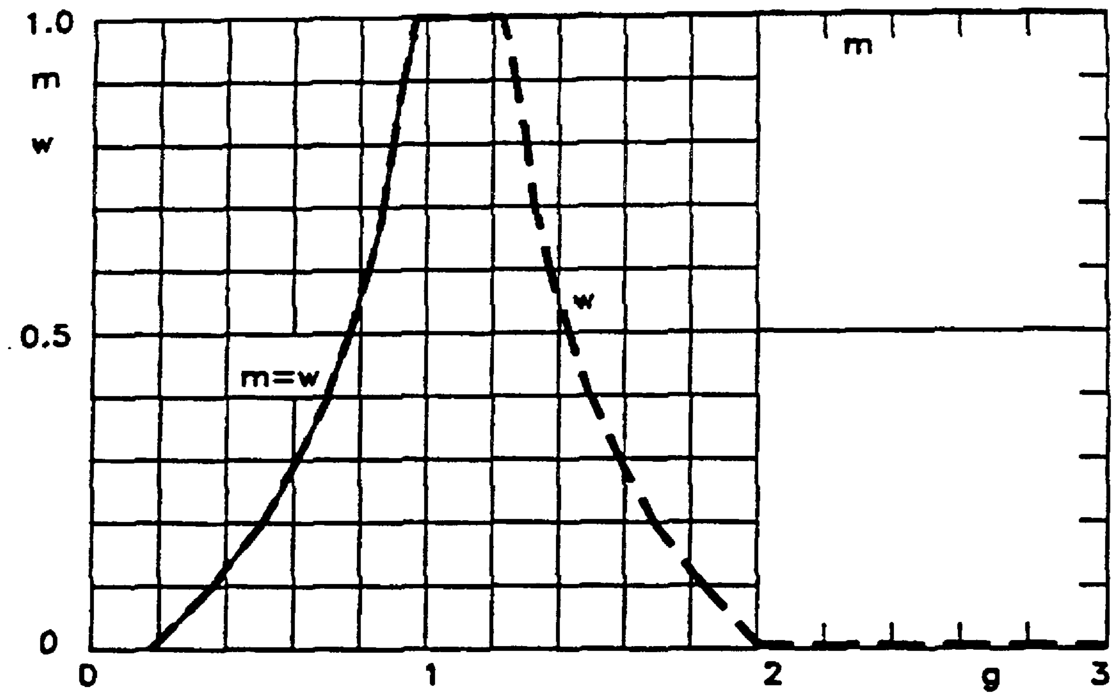


Figure 34—Values of exponents *m* and *w* for air density correction and *w* for humidity correction as a function of parameter *g*

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 appropriate apparatus committee with reference to the requirements of particular classes of apparatus. In those cases where 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 dummies unless the appropriate apparatus committee states otherwise, in which case they shall specify the test procedure to be used.

It is left to the appropriate apparatus standard to specify whether or not corrections have to be applied to the voltage values in those cases where both external and internal insulations are involved.

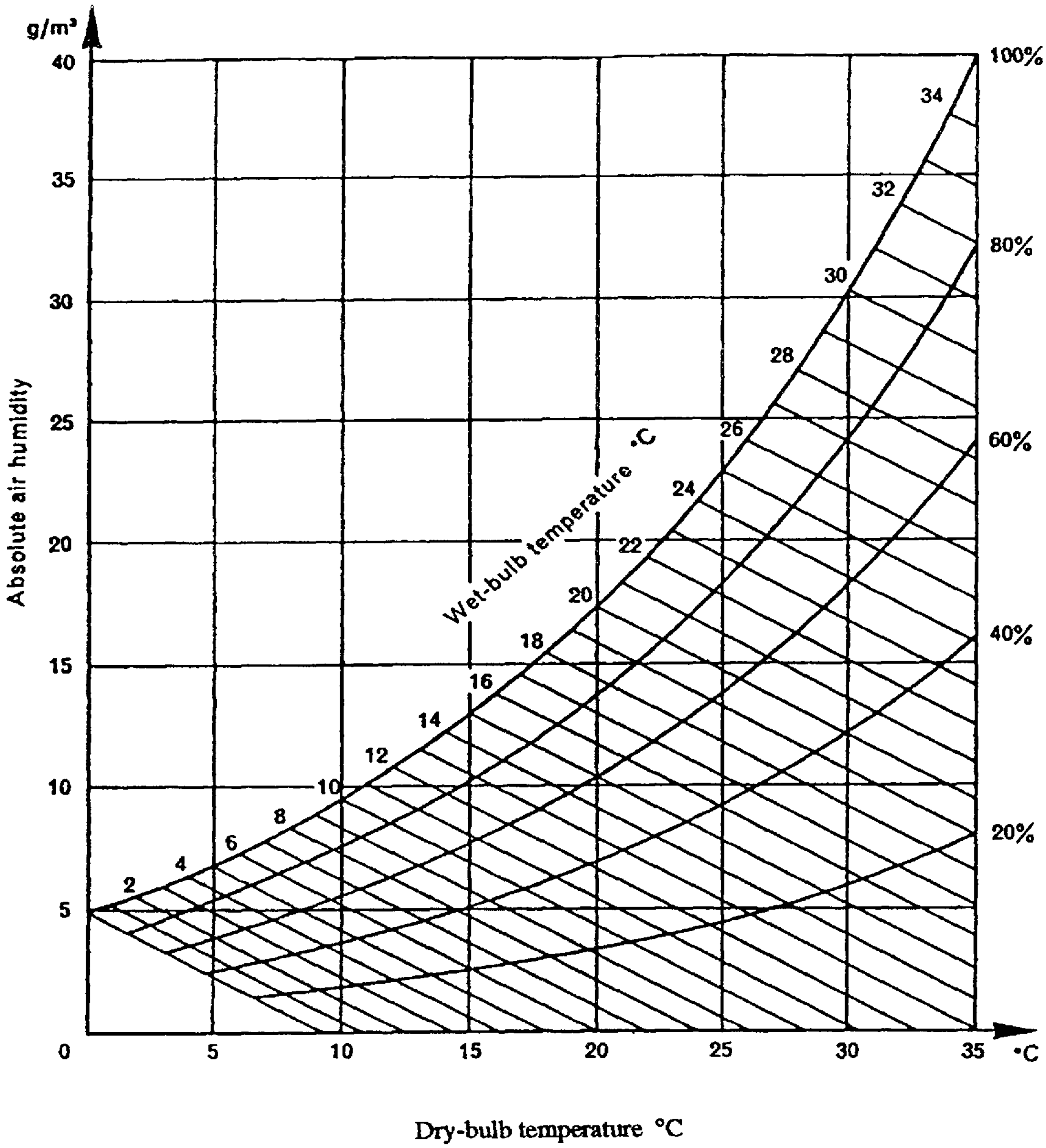
17. Voltage measurement by means of sphere gaps and rod gaps

17.1 Overview

17.1.1 Applicability and objective

This clause is applicable to the use of the sphere gap for the measurement of the peak value of

a) Alternating voltages
b) Lightning impulse voltages
c) Switching impulse voltages
d) Direct voltages



NOTE—Curves of percentage relative humidity are also given.

Figure 35—Absolute humidity of air as a function of dry- and wet-bulb thermometer readings (standard pressure only)

This clause is also applicable to the use of rod gaps for the measurement of direct voltage. Data are also given on rod-gap flashover levels for impulse voltages for information.

The objectives of this clause are to

- — Describe the geometry of the standard sphere gap
- — Define the connections of the sphere gap
- — Outline the use of the sphere gap
- — Provide the sphere-gap disruptive discharge voltage data and the tolerances or the accuracy
- — Describe the geometry of rod gaps and outline their use

17.2 Standard sphere gap

17.2.1 Definition

The standard sphere gap is a peak-voltage measuring device constructed and arranged in accordance with this standard. It consists of two metal spheres of the same diameter, D, with their shanks, operating gear, insulating supports, supporting frame, and leads for connections to the point at which the voltage is to be measured. Standard values of D are 62.5 mm, 125 mm, 250 mm, 500 mm, 750 mm, 1000 mm, 1500 mm, and 2000 mm. The spacing between the spheres is designated as S.

The points on the two spheres that are closest to each other are called the sparking points. In practice, the disruptive discharge may occur between other neighboring points.

Two arrangements, one of which is typical of sphere gaps with a vertical axis and the other, of sphere gaps with a horizontal axis, are shown in figures 36 and 37 respectively.

NOTE—The sphere shanks shall be reasonably in line, whichever arrangement of gap is used.

17.2.2 Requirements for the spheres

17.2.2.1 Tolerances

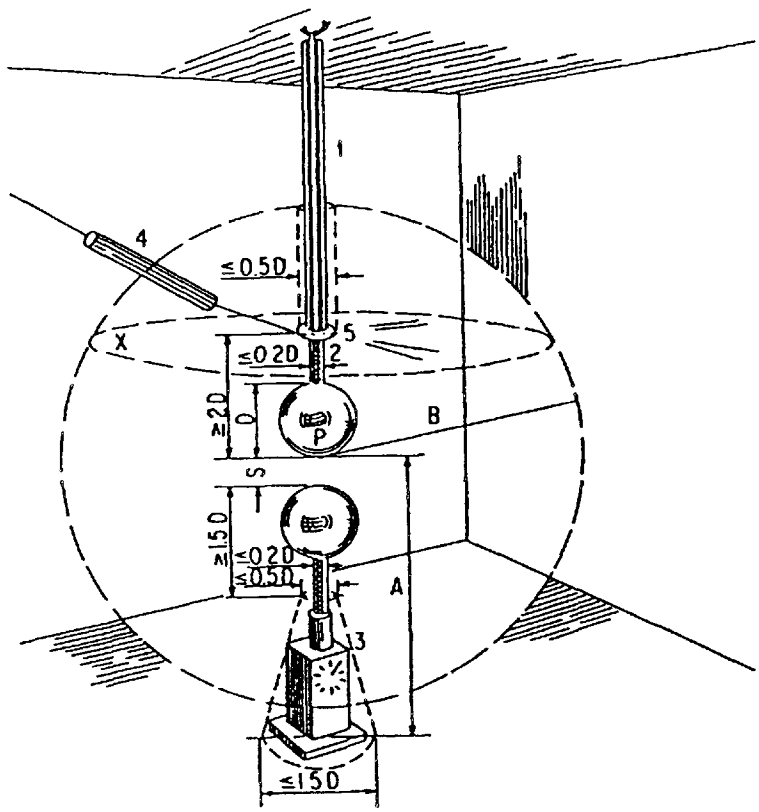
The spheres shall be carefully made so that their surfaces are smooth and their curvature is as uniform as possible.

The requirements on their shapes are as follows:

a) *General shape.* The diameter of each sphere shall nowhere differ by more than 2% from the nominal value.

b) *Freedom from surface irregularities in the region of the sparking point.* The spheres shall be reasonably free from surface irregularities in the region of the sparking point. This region is defined by a circle such as would be drawn on the spheres by a pair of dividers set to an opening of $0.3D$ and centered on the sparking point.

   The freedom from surface irregularities is checked by a spherometer, the feet of which are between $0.125D$ and $0.25D$ apart. The spherometer measures the distance H of its central point from the plane passing through the three feet of the instrument, which form an equilateral triangle of side a. When the three feet and the central point are in contact with a perfectly spherical surface of radius $D/2$, the following value is obtained for H:



1) Insulating support
2) Sphere shank
3) Operating gear, showing maximum dimensions
4) High-voltage connection with series resistor
5) Stress distributor, showing maximum dimensions

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

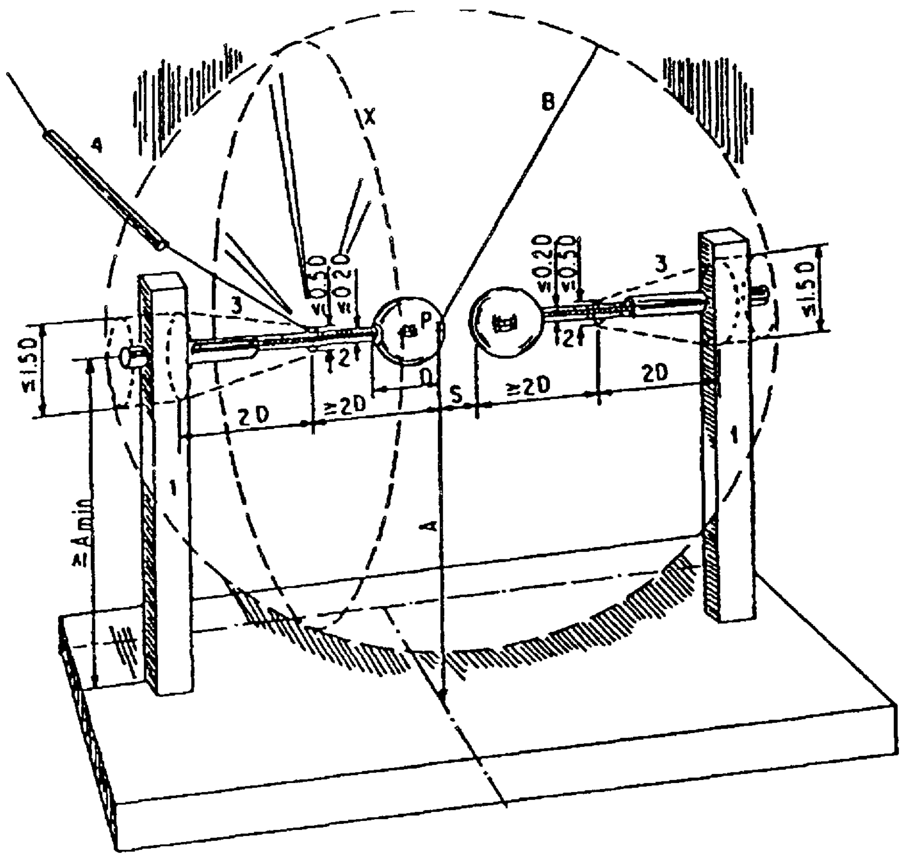
NOTE—The figure is drawn to scale for a 100 cm sphere gap at radius spacing.

Figure 36—Vertical sphere gap

$$H = \frac{D}{2} - \frac{1}{2}\sqrt{D^2 - \frac{4}{3}a^2} \qquad (59)$$

or, with adequate accuracy,

$$H = \frac{D}{3}\left[\left(\frac{a}{D}\right)^2 + \frac{1}{3}\left(\frac{a}{D}\right)^4\right] \qquad (60)$$



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 37—Horizontal sphere gap

The measured values may differ from these equations. When the feet of the spherometer are placed in various positions in the region defined in item b), the difference between the measured values of H and the value given in the equation shall nowhere exceed

1) 0.1% of the diameter D if this is less than or equal to 1000 mm
2) 0.2% of the diameter D if this is greater than 1000 mm

If the spherometer is not available, flat circular gauges may be used for an approximate evaluation of irregularities of the surface.

NOTE—The tolerances on size and shape need usually only be checked in the manner described in the preceding paragraphs when the spheres are first supplied. It will normally be sufficient to make subsequent examinations by feeling the spheres or inspecting them visually.

17.2.2.2 State of the surfaces

The surfaces of the spheres in the neighborhood of the sparking points shall be free from any trace of varnish, grease, or other protective coating. They shall be clean and dry but need not be polished. If the spheres become excessively roughened or pitted in use, they shall be reburnished or replaced.

NOTE—If the relative humidity of the air exceeds approximately 90%, moisture may condense on the surface and the measurements will then cease to be accurate.

17.2.3 Construction of the shanks of the spheres

17.2.3.1 Vertical gap

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 $0.2D$ 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 is used at the end of the shank, its greatest dimension perpendicular to the axis of the spheres shall not exceed $0.5D$. Such stress distributors shall be at least $2D$ from the sparking point of the high-voltage sphere. The grounded shank and the operating gear have a smaller effect and their dimensions are therefore less important. Limits on the size of the components of a typical vertical sphere gap are given in figure 36.

17.2.3.2 Horizontal gap

When the spheres are arranged horizontally, the limiting dimensions of a typical sphere are given in figure 37. They are the same for both sides of the gap.

17.2.4 Height of spheres above the horizontal ground plane

The sphere gap should be used above a horizontal ground plane such as the conducting network in or on the floor of the laboratory or a conducting surface on the support on which the sphere gap is to be placed. The height A of the sparking point of a high-voltage sphere above such a ground plane shall be within the limits given in table 7 of 17.2.5. This requirement applies both to the vertical and horizontal gaps.

If the sphere gap is mounted with the grounded sphere nearer to the ceiling and if other surfaces such as walls and the floor are at a considerably greater distance, then the ceiling may be regarded as the horizontal plane, from which the distance A is measured downwards.

17.2.5 Clearance around the spheres

The distance from the sparking point of the high-voltage sphere to any extraneous objects (such as walls, ceilings, transformer tanks, bushings, impulse generators, etc.) and also to the supporting framework for the spheres if this is not made of conducting material shall not be less than the value of B in table 7. Except as permitted in the following paragraph, B should not be less than $2D$, regardless of the value of S.

Supporting frameworks for the spheres made of insulating material are exempt from this stipulation provided they are clean and dry and the spheres are used for 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 7, but it shall not be below $1.6D$.

NOTES

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 should, 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 tables 8 and 9 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.

2—For the measurement of very high voltages, it may be necessary to increase *A* and *B* above the minimum values given in table 7, as these are not always sufficient to prevent disruptive discharge to grounded objects, especially those with sharp edges or corners.

Table 7—Clearance around the spheres

Sphere diameter *D* (mm)	Minimum value of *A*	Maximum value of *A*	Minimum value of *B*
62.5	7*D*	9*D*	14*S*
125	6*D*	8*D*	12*S*
250	4*D*	7*D*	10*S*
500	4*D*	6*D*	8*S*
750	4*D*	6*D*	8*S*
1000	3.5*D*	5*D*	7*S*
1500	3*D*	4*D*	6*S*
2000	3*D*	4*D*	6*S*

17.3 Connections of the sphere gap

17.3.1 Grounding

One sphere shall preferably be connected directly to ground, but it may be connected through a resistor for special purposes. In the interests of personnel safety, however, such resistors should be of very low values.

17.3.2 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* away 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 live 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. The plane is shown in figures 36 and 37.

17.3.3 Protective series resistance in the measurement of alternating and direct voltages

Precautions should be taken to minimize pitting of the spheres and to prevent superimposed oscillations that may cause erratic disruptive discharges. For this purpose, a resistance of from 100 000 Ω to 1 MΩ should be inserted in series with the sphere gap. This range of resistance values applies to measurements of direct voltages and of alternating voltages at power frequencies. For alternating voltages of higher frequencies, where the effect of the voltage drop in the resistance due to the charging current of the gap may become appreciable, this resistance should be suitably reduced.

The resistor is to be placed as near as possible to the gap, usually in series with the high-voltage sphere. It should not be placed in the common connection from the voltage source to the sphere gap and to the test object.

When brush discharges are present in the test circuit, series resistance is specially important in order to reduce the effect of the consequent transient overvoltage on the operation of the sphere gap. When these discharges are not present either in the test circuit or in the test specimen, the resistance may be reduced to a value fixed by the permissible burning of the spheres by disruptive discharges.

17.3.4 Protective series resistance in the measurement of impulse voltages

Normally, no resistance is connected in series with the sphere gap when used for measuring impulse voltages. However, in some cases, series resistance may have a purpose. One purpose that is especially applicable to spheres of large diameters is to eliminate oscillations in the sphere-gap circuit, which may cause a higher voltage to occur between the spheres than on the test specimen. For spheres of smaller diameter, this phenomenon is generally of minor importance.

The value of the resistance should not exceed 500 Ω. It is essential for the reduction of oscillations that the resistance should be of low inductance (not more than 30 μH). For the position of the resistor in the circuit, see 17.3.3.

17.4 The use of the sphere gap

17.4.1 Irradiation

The disruptive discharge voltage of a sphere gap is affected by the ionization in the gap between the spheres at the moment of application of the voltage. The values given in tables 8 and 9 apply to measurements made without irradiation, apart from any random ionization already present, except in

a) The measurement of voltages below 50 kV peak, whatever the sphere diameter
b) The measurement of voltages with spheres of 125 mm diameter and less, whatever the voltage

For measurements under conditions a) and b), extra irradiation is recommended and is sometimes essential if accurate and consistent results are to be obtained. This is of special importance in the measurement of impulse voltages and for all types of voltages where very small spacings are used.

The irradiation may be obtained by a capsule containing radioactive material having an activity of not less than 0.2 mCi and preferably of about 0.6 mCi inserted in the high-voltage sphere near the sparking point. Another method is the irradiation of the gap by a quartz-tube mercury-vapor lamp having a minimum rating of 35 W and a current of at least 1 A. The lamp should be placed at about the distance *B* given in table 8, and the light should fall on the sparking points of the spheres.

In the measurement of impulse voltages, the irradiation provided by the discharge in the gaps of the impulse generator has also been found satisfactory.

NOTES

1—The usual precautions should be taken in handling radioactive materials, which should be kept in a lead container except when in actual use.

2—1 curie (Ci) is defined as 3.7×10^{10} disintegrations per second, which is equivalent to the activity of 1 g of radium.

17.4.2 Voltage measurements

The procedure usually consists in establishing a relation between a high voltage, as measured by the sphere gap, and the indication of a voltmeter, an oscilloscope, or other device connected in the control circuit of the equipment. Unless the contrary can be shown, this relation ceases to be valid if the circuit is altered in any respect other than a slight change of the spacing of the spheres. The voltage measured by the sphere gap is derived from the spacing. The procedure in establishing the relationship varies with the type of voltage to be measured, as discussed in the following subclauses.

17.4.2.1 Measurement of direct and alternating voltages

The voltage shall be applied with an amplitude low enough not to cause disruptive discharge during the switching transient, 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. Alternatively, a constant voltage may be applied across the gap and the spacing between the spheres slowly reduced until disruptive discharge occurs.

If there is dust or fibrous material in the air, numerous low and erratic disruptive discharges may occur, especially when direct voltages are being measured. It may be necessary to carry out a large number of tests before consistent results can be obtained.

The final measurement should be the mean of three successive readings agreeing within 3%.

17.4.2.2 Measurement of impulse voltages

In order to obtain the 50% disruptive-discharge voltage of a sphere gap, the spacing of the gap or the charging voltage of the impulse generator shall be adjusted in steps corresponding to not more than 2% of the expected disruptive-discharge value. Six applications of the impulse should be made at each step. The interval between applications shall not be less than 5 s. The value giving 50% probability of disruptive discharge is preferably obtained by interpolation between at least two gap or voltage settings, one resulting in two disruptive discharges or less, and the other in four disruptive discharges or more.

Another, less accurate, method is to adjust the settings until four to six disruptive discharges are obtained in a series of ten successive applications.

17.5 Sphere-gap disruptive-discharge voltages

17.5.1 Numerical values in tables 8 and 9

The disruptive-discharge voltages for various spacings between the spheres are given in tables 8 and 9. These were based on IEC Publication 52 (1960) and extended to a spacing equal to diameter D. Table 8 gives disruptive voltages (50% values in impulse tests) in kilovolts peak. This table has been derived from experiments and is presumed to be accurate within these limits:

a) Alternating voltages (≤ 1700 kV peak)
b) Negative lightning impulse voltages (≥ 10 kV peak and ≤ 2410 kV peak)
c) Negative switching impulse voltages (≥ 10 kV peak and ≤ 2410 kV peak)
d) Direct voltages of either polarity (negative ≤ 1300 kV; positive ≤ 800 kV)

Table 9 gives 50% disruptive-discharge voltages in kilovolts peak for positive lightning impulse voltages and positive switching impulse voltages and is presumed to be accurate up to 2580 kV peak.

17.5.2 Accuracy of tables 8 and 9

17.5.2.1 Alternating and impulse voltages

For spacings up to 0.5*D*, the tables are considered to be accurate within ±3%. Values in the tables for spacings between 0.5*D* and 1.0*D* are regarded as of less accuracy and, for that reason, are put in parentheses.

17.5.2.2 Direct voltages

The measurement of direct voltages is generally subject to larger errors than that of alternating or impulse voltages. Such errors are usually caused by dust or fibers in the air. There is also a tendency for abnormally low disruptive discharge values to be obtained if the voltage is maintained for a long time. It is considered that, in the absence of excessive dust, the results will be accurate within ±5% provided that the spacing is not greater than about 0.4*D*.

NOTE—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 0.05D.

17.5.3 Influence of atmospheric conditions

17.5.3.1 Atmospheric conditions valid for the tabulated values

The tabulated values are valid for the reference atmospheric conditions corresponding to an ambient temperature of 20 °C and an atmospheric pressure of 101.3 kPa (760 mmHg).

17.5.3.2 Atmospheric correction factor

To determine the flashover voltages for a given sphere-gap arrangement when atmospheric conditions are not at the reference level, multiply the values in tables 8 and 9 by the correction factor in table 10, using equation (56) to calculate the relative air density δ.

Table 8—Sphere gap with one sphere grounded

Peak values of disruptive-discharge voltages (50% for impulse tests) are valid for alternating voltages, negative lightning impulse voltages, negative switching impulse voltages, and direct voltages of either polarity

Sphere-gap spacing (mm)	Voltage (kV peak)		
	Sphere diameter (cm)		
	6.25	12.5	25
5	17.2	16.8	–
10	31.9	31.7	–
15	45.5	45.5	–
20	58.5	59.0	–

Table 8—Sphere gap with one sphere grounded *(continued)*

Peak values of disruptive-discharge voltages (50% for impulse tests) are valid for alternating voltages, negative lightning impulse voltages, negative switching impulse voltages, and direct voltages of either polarity

Sphere-gap spacing (mm)	Voltage (kV peak)		
	Sphere diameter (cm)		
	6.25	12.5	25
25	69.5	72.5	72.5
30	79.5	85.0	86.0
35	(87.5)	97.0	–
40	(95.0)	108	112
45	(101)	119	–
50	(107)	129	137
55	(112)	138	–
60	(116	146	161
62.5	(117)	150	–
70	–	(161)	184
80	–	(174)	206
90	–	(185)	226
100	–	(195)	244
110	–	(203)	261
120	–	(212)	275
125	–	(214)	282
150	–		(314)
175	–		(342)
200	–		(366)
225	–		(385)
250	–		(400)

Sphere-gap spacing (mm)	50	75	100	150	200
50	138	138	–	–	–
75	202	203	–	–	–

Table 8—Sphere gap with one sphere grounded *(continued)*

Peak values of disruptive-discharge voltages (50% for impulse tests) are valid for alternating voltages, negative lightning impulse voltages, negative switching impulse voltages, and direct voltages of either polarity

Sphere-gap spacing (mm)	Voltage (kV peak)				
	Sphere diameter (cm)				
	50	75	100	150	200
100	263	265	266	266	266
125	320	327	–	–	–
150	373	387	390	–	–
175	420	443	–	–	–
200	460	492	510	510	510
250	530	585	615	–	–
300	(585)	665	710	745	750
350	(630)	735	800	–	–
400	(670)	(800)	875	955	975
450	(700)	(850)	(945)	–	–
500	(730)	(895)	(1010)	1130	1180
600	–	(970)	(1110)	1280	1340
700	–	(1025)	(1200)	1390	1480
750	–	(1040)	(1230)	1440	1540
800	–	–	(1260)	(1490)	1600
900	–	–	(1320)	(1580)	1720
1000	–	–	(1360)	(1660)	1840
1100	–	–	–	(1730)	(1940)
1200	–	–	–	(1800)	(2020)
1300	–	–	–	(1870)	(2100)
1400	–	–	–	(1920)	(2180)
1500	–	–	–	(1960)	(2250)
1600	–	–	–	–	(2320)
1700	–	–	–	–	(2370)

Table 8—Sphere gap with one sphere grounded *(continued)*

Peak values of disruptive-discharge voltages (50% for impulse tests) are valid for alternating voltages, negative lightning impulse voltages, negative switching impulse voltages, and direct voltages of either polarity

Sphere-gap spacing (mm)	Voltage (kV peak)				
	Sphere diameter (cm)				
	50	75	100	150	200
1800	–	–	–	–	(2410)
1900	–	–	–	–	(2460)
2000	–	–	–	–	(2490)

NOTE—The figures in parentheses, which are for spacings of more than 0.5*D*, will be within 5% if the maximum clearances in 17.2.5 are met. For errors for direct voltages, see 17.5.2.2.

Table 9—Sphere gap with one sphere grounded

Peak values of distruptive-discharge voltages (50%) are valid for positive lightning impulses and positive switching impulses

Sphere-gap spacing (mm)	Voltage (kV peak)		
	Sphere diameter (cm)		
	6.25	12.5	25
5	17.2	16.8	–
10	31.9	31.7	–
15	45.9	45.5	–
20	59.0	59.0	–
25	71.0	72.5	72.7
30	82.0	85.0	86.0
35	(91.5)	98.0	–
40	(101)	110	112
45	(108)	122	–
50	(115)	134	138
55	(122)	145	–

Table 9—Sphere gap with one sphere grounded *(continued)*

Peak values of distruptive-discharge voltages (50%) are valid for positive lightning impulses and positive switching impulses

Sphere-gap spacing (mm)	Voltage (kV peak)		
	Sphere diameter (cm)		
	6.25	12.5	25
60	(127)	155	163
62.5	(128)	160	–
70	–	(173)	187
80	–	(189)	211
90	–	(203)	233
100	–	(215)	254
110	–	(229)	273
120	–	(234)	291
125	–	(239)	299
150	–	–	(337)
175	–	–	(368)
200	–	–	(395)
225	–	–	(416)
250	–	–	(433)

Sphere-gap spacing (mm)	50	75	100	150	200
50	138	138	–	–	–
75	202	202	–	–	–
100	263	265	266	266	266
125	323	327	–	–	–
150	380	387	390	–	–
175	432	447	–	–	–
200	480	505	510	510	510
250	555	605	620	–	–
300	(620)	695	725	745	750

Table 9—Sphere gap with one sphere grounded ***(continued)***

Peak values of distruptive-discharge voltages (50%) are valid for positive lightning impulses and positive switching impulses

Sphere-gap spacing (mm)	Voltage (kV peak)				
	Sphere diameter (cm)				
	50	75	100	150	200
350	(670)	770	815	–	–
400	(715)	(835)	900	965	980
450	(745)	(890)	980	–	–
500	(775)	(940)	1040	1150	1190
600	–	(1020)	(1150)	1310	1380
700	–	(1070)	(1240)	(1430)	1550
750	–	(1090)	(1280)	(1480)	1620
800	–	–	(1310)	(1530)	1690
900	–	–	(1370)	(1630)	1820
1000	–	–	(1410)	(1720)	1930
1100	–	–	–	(1790)	(2030)
1200	–	–	–	(1860)	(2120)
1300	–	–	–	(1930)	(2200)
1400	–	–	–	(1980)	(2280)
1500	–	–	–	(2020)	(2350)
1600	–	–	–	–	(2410)
1700	–	–	–	–	(2470)
1800	–	–	–	–	(2510)
1900	–	–	–	–	(2550)
2000	–	–	–	–	(2590)

NOTE—The figures in parentheses, which are for spacings of more than 0.5*D*, will be within ±5% if the maximum clearances in 17.2.5 are met.

Conversely, to set a sphere gap to flash over at some specified voltage when atmospheric conditions are not at the reference level, divide the specified voltage by the correction factor in table 10 and then find the gap spacing corresponding to this corrected voltage using tables 8 and 9.

Table 10—Correction factors

Relative air density (δ)	Correction factor
0.70	0.72
0.75	0.77
0.80	0.82
0.85	0.86
0.90	0.91
0.95	0.95
1.00	1.00
1.05	1.05
1.10	1.09
1.15	1.13

The disruptive-discharge voltage of a sphere gap increases with increasing humidity of the air. The numerical value of the effect is uncertain, but it is unlikely to be more than 2% or 3% over the range of humidities normally encountered in laboratories. Because of this uncertainty, no correction factor for humidity can be given at present.

17.6 Use of a rod-rod gap for measuring direct voltage

17.6.1 General arrangement of a rod-rod gap

The general arrangement of a rod-rod gap shall be as shown in either figure 38 (vertical gap) or figure 39 (horizontal gap).

The rods shall be made of steel or brass, shall have a square section with each side between 15 mm and 25 mm, and shall have a common axis. The ends shall be cut at right angles to the axis, leaving the edges sharp.

The clearance from the tip of the high-voltage rod to earthed objects and walls, other than the ground plane, shall not be less than 5 m.

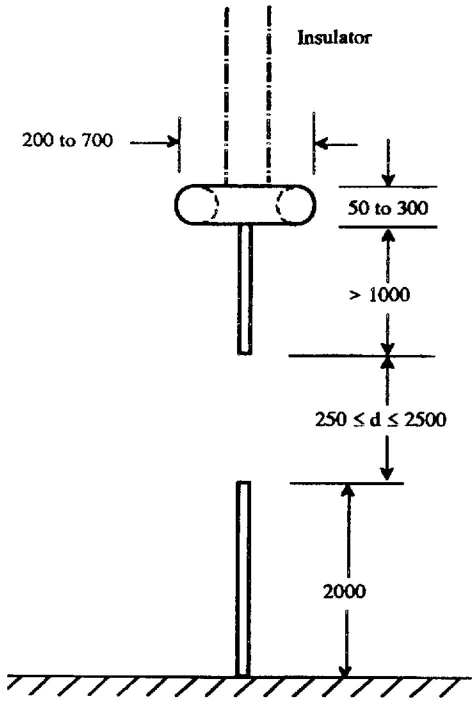
17.6.2 Reference values

The disruptive-discharge voltage for positive and negative direct voltage at standard reference atmosphere for either the vertical or horizontal gap is given by

$$V_O = 2 + 0.534d \qquad (61)$$

$250 \text{ mm} \leq d \leq 2500 \text{ mm}$

$1 \text{ g/m}^3\ h/\delta \leq 13 \text{ g/m}^3$



NOTE—All dimensions are in millimeters.

Figure 38—Vertical arrangement of a rod-rod gap

where

V_0	is the disruptive-discharge voltage (in kilovolts)
d	is the gap spacing (in millimeters)
h	is the absolute humidity (in g/m^3)
δ	is the relative air density

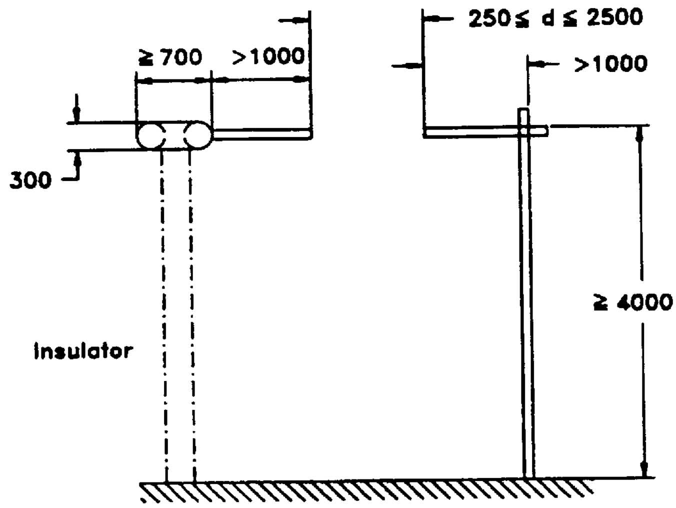
Under these conditions, the measured uncertainty is estimated to be less than ±3%.

The rod-rod gap shall not be used as an approved measuring device at gap spacings 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.

17.6.3 Calibration procedure for a nonapproved measuring device

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 disruptive-discharge voltage is about 1 min.

Ten readings of the voltage at the instant of sparkover shall be taken with the nonapproved measuring device under calibration. The voltage, at standard reference atmosphere, corresponding to the mean of these ten values is given by equation (65). This voltage shall be corrected for the actual atmospheric conditions in accordance with clause 16.



NOTE—All dimensions are in millimeters.

Figure 39—Horizontal arrangement of a rod-rod gap

17.7 Rod-rod gap sparkover data for impulse voltages

Volt-time sparkover data on rod gaps for impulse voltages have not been standardized and are given in this subclause for information only. These data apply to a specific rod-gap configuration. The rod gap consists of two 12.5 mm square rod electrodes, each cut off squarely and mounted horizontally on supports so that a length of rod equal to or greater than one-half the gap spacing overhangs the inner edge of the support. The height of the rods above the ground plane should be at least 1.3 times the gap spacing plus 10 cm. Sparkover values for rod gaps under standard atmospheric conditions are given in table 11. Rod-gap sparkover voltage varies with air density and humidity, and it can be corrected using the procedures given in clause 16.

Table 11—Rod-rod gap sparkover peak voltages

Gap spacing (cm)	60 Hz (kV peak)	Critical sparkover (kV peak)			
		1.2 × 5 μs) wave (nonstandard)		(1.2 × 50 μs) wave	
		Positive	Negative	Positive	Negative
2	25	33	33	31	31
3	36	43	43	41	41
4	46	52	52	50	50
5	53	61	63	59	61
6	60	66	71	64	69
8	70	81	87	75–76*	84
10	79	96	104	87–91*	99

Table 11—Rod-rod gap sparkover peak voltages *(continued)*

Gap spacing (cm)	60 Hz (kV peak)	Critical sparkover (kV peak)			
		1.2 × 5 µs) wave (nonstandard)		(1.2 × 50 µs) wave	
		Positive	Negative	Positive	Negative
12	86	115	121	100–107*	116
14	95	134	138	114–125*	132
16	104	153	155	129–142*	147
18	112	170	171	139–153*	158
20	120	188	188	154–161*	176
25	143	234	232	184	217
30	167	277	274	217	249–260*
35	192	320	316	250	283–306*
40	218	362	358	281	313–348*
45	243	405	405	309	347–375*
50	270	445	449	339	382–392*
60	322	525	535	392	455
70	374	605	625	450	525
80	422	690	710	510	585
90	473	765	790	570	670
100	520	845	880	625	715
120	625	990	1040	735	835
140	720	1150	1120	850	965
160	820	1310	1390	965	1090
180	920	1490	1580	1100	1240
200	1020	1610	1620	1195	1340
220	1125	1770	1890	1300	1470
240	–	1930	2070	1430	1605

*Dual values are due to unstable conditions, the cause being unknown. The error in rod-gap sparkover voltage can be as large as ±8%.

18. Reference voltage divider

18.1 Introduction

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.

18.2 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 40.

18.2.1 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 are provided in table 12.

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

18.2.2 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.

18.3 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.

Table 12—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)

Table 12—Winding data for reference divider *(continued)*

Description	Details
Turns per layer	1100
Winding pitch	0.24 mm (0.0095 in)
Turns per centimeter (inch)	41.3 (105)
Layer insulation	0.13 mm (0.005 in) Mylar® tape
Total mass	37 g (1.3 oz)
Wire length	177 m (580 ft)

18.4 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).

18.5 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.

18.6 Response parameters

The resulting divider should have response parameters in accordance with 13.4.4.

These response time values are given for guidance only. Supporting data are not available at this time to determine the precise requirements for response parameter values.

19. Statistical treatment of test results

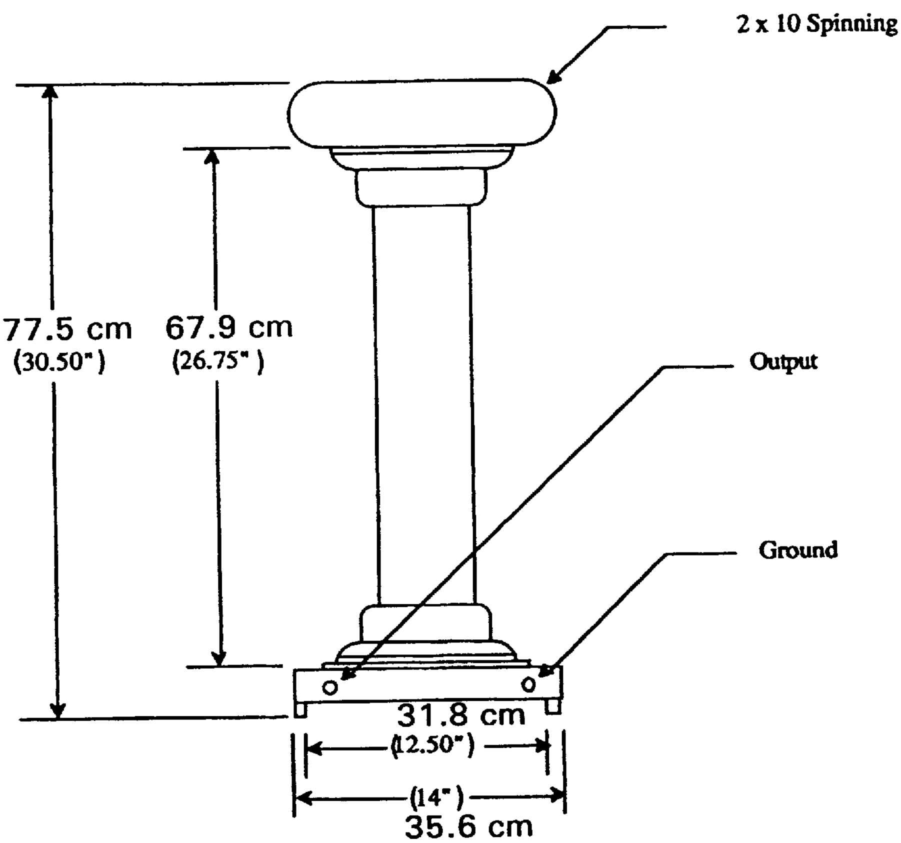
19.1 Classification of tests

Disruptive-discharge test procedures can be divided into three classes for the purpose of statistical evaluation.

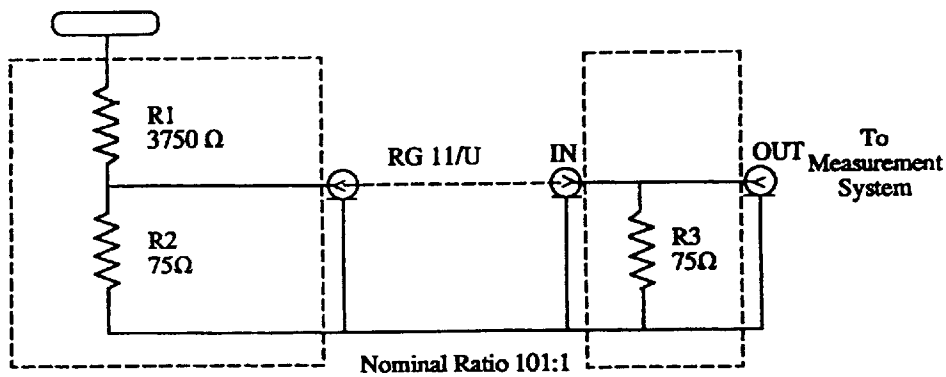
19.1.1 Class 1: multiple-level tests

In a Class 1 test, m_i substantially equal voltage stresses (e.g., lightning impulses) are applied at each of n voltage levels V_i ($i = 1, 2, ..., n$). While this procedure is usually employed with impulse voltages, some tests with alternating and direct voltages also fall into this class.

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.



a) Outline drawing



b) Schematic

Figure 40—Reference voltage divider

19.1.2 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. 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 $n = \Sigma k_i$.

19.1.3 Class 3: successive discharge 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 is observed. The results are the n values of voltage V_i or time t_i at which the disruptive discharge occurred.

Such tests are made with direct, alternating, or impulse voltages. Tests where disruptive discharges occur on the front of the impulse fall into this class.

19.2 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 function, the disruptive-discharge probability function, can be represented mathematically by expressions depending on 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 $p(V) = 0.16$.

NOTES

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.

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 found from tests with very large 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.

19.2.1 Confidence limits and statistical error

Confidence limits of a parameter y are some arbitrarily selected upper (y_U) and lower (y_L) values for the parameter y. If the experimentally obtained values of the parameter y are 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 half-width $e_r = (y_U - y_L)/2$ of the confidence band is called the statistical error.

Usually C is taken as 0.95 (or 0.90), and the corresponding limits are called the 95% (or 90%) confidence limits.

The statistical error (e_r) 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.

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 statistical error (e_r) may be combined with estimates of other errors (e.g., measuring errors) to define the overall error for the determination of a particular parameter.

19.3 Analysis of test results

This subclause is applicable to cases where 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.

19.3.1 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:

$$p(V) = \frac{1}{z\sqrt{2\pi}} \int_{-\infty}^{V} e^{-\frac{1}{2}\left(\frac{x - V_{50}}{z}\right)^2} dv \qquad (62)$$

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 19.4) 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 statistical error 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

$$(V^*_{50} - 0.75z^*) \leq V_{50} \leq (V^*_{50} + 0.75z^*) \tag{63}$$

and for z

$$0.4z^* \leq z \leq 2.0z \tag{64}$$

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 statistical error tends towards lower values for estimates of V_p in the vicinity of $p = 0.5$ or 50%.

19.3.2 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

$$V^*_p = \frac{\Sigma (k_i V_i)}{n} \tag{65}$$

where

k_i is the number of groups of stresses applied at the voltage level V_p

For a more accurate formula, see the technical literature.

To avoid appreciable errors, the lowest voltage level taken into account should not differ from V_p by more than $2\Delta V$.

The withstand procedure described in 19.1.2 provides an estimate of V_p for a disruptive discharge probability p given by

$$p = 1 - (0.5)^{1/m} \tag{66}$$

while the discharge procedure gives V_p for

$$p = (0.5)^{1/m} \tag{67}$$

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.

$m =$	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.

19.3.3 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 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

$$V^*_{50} = \frac{\Sigma V_i}{n} \tag{68}$$

$$z^* = \left[\Sigma \frac{(V_i - V_{50})^2}{(n-1)}\right]^{1/2} \tag{69}$$

For other distributions, likelihood methods can be employed to estimate V_{50} and z (see 19.4). The same expressions and methods apply in cases where times to the occurrence of a disruptive discharge (t_i) are to be analyzed.

The confidence limits for Gaussian distributions 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

$$(V^*_{50} - 0.47z^*) \le V_{50} \le (V^*_{50} + 0.47z^*) \tag{70}$$

and

$$0.76z^* \le z \le 1.46z^* \tag{71}$$

19.4 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 $p(V; V_{50}, z)$ 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.

19.4.1 The likelihood function

For Class 1 and Class 2 tests, the numbers of discharges, d_i, and the numbers of withstands, w_i, found at each voltage level V_i are known. If the form of the discharge probability distribution function $p(V; V_{50}, z)$ is known or assumed, the probability of a discharge at the level V_i is $p(V; V_{50}, z)$ and the probability of a withstand is $[(1 - p(V; V_{50}, z)]$. The likelihood function L_i corresponding to d_i discharges and w_i withstands occurring at a voltage level V_i is then

$$L = p(V_i; V_{50}, z)^{d_i}[1 - p(V_i; V_{50}, z)]^{w_i} \tag{72}$$

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

$$L = L_1 L_2 \ldots L_i \ldots L_n = L(V_{50}, z) \tag{73}$$

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

$$L = f(V_i; V_{50}, z)^{m_1} f(V_2; V_{50}, z)^{m_2} \ldots f(V_m; V_{50}, z)^{m_m} \tag{74}$$

where

$$f = \frac{dp}{dV}$$

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.

19.4.2 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 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.

20. Bibliography

[B1] AFNOR C85 (1944), Regles pour la Mesure des Tensions au Moyen de l'Eclateur a Spheres.

[B2] BSI Publication 358 (1960), Method for Measurement of Voltages with Sphere-Gaps.

[B3] DIN-5730 (1950), Reglen für Spannungs Messungen mit der Kugelfunkenstrecke.

[B4] IEC Publication 52 (1960), Recommendations for voltage measurement by means of sphere-gaps (one sphere earthed).

[B5] IEC Publication 60-1 (1989), High voltage test techniques—Part 1: General definitions and test requirements.

[B6] IEC Publication 507 (1991), Artificial pollution tests on high-voltage insulators to be used on a.c. systems.

[B7] IEC Publication 1245 (1993), Artificial pollution tests on high-voltage insulators to be used on d.c. systems.

[B8] Abdullah, M. and Kuffel, E., "Development of Spark Discharge in Non-Uniform Field Gaps Under Impulse Voltages," *Proceedings of the Institution of Electrical Engineers*, vol. 112, no. 5, pp. 1018–1024, May 1965.

[B9] AIEE Subcommittee, "Revised Sphere Gap Sparkover Voltages," *AIEE Transactions*, vol. 55, p. 783, July 1936.

[B10] AIEE Working Group on Definitions, "Definitions of Terms Related to Corona," *IEEE Transactions on Power Apparatus and Systems*, vol. 82, pp. 1044–1050, Dec. 1963.

[B11] Arndt, F., "Impulse Voltage Measuring Instruments," *ETZ* (ed. B), vol. 23, no. 13, pp. 305–306, June 25, 1971.

[B12] Asner, A., "Progress in Measurement of Very High, Rapidly Changing Impulse Voltages," *Brown Boveri Review*, vol. 47, no. 4, Apr. 1960.

[B13] Bartnikas, R., "Some Observations on the Character of Corona Discharges in Short Gap Spaces," *IEEE Transactions on Electrical Insulation*, vol. EI-6, no. 2, pp. 63–75, June 1971.

[B14] Bellaschi, P. L., "Impulse Test Requirements for Generator Transformers and for Tertiary Windings," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-88, no. 8, pp. 1183–1186, Aug. 1969.

[B15] Bellaschi, P. L., "The Measurement of High-Surge Voltages," *AIEE Transactions*, vol. 52, pp. 544–552, June 1933.

[B16] Bellaschi, P. L. and McAuley, P. H., "Impulse Calibration of Sphere Gaps," *Electric Journal*, vol. 31, pp. 228–232, 1934.

[B17] Bellaschi, P. L., and Teague, W. L., "Sphere-Gap Characteristics of Very Short Impulses," *Electric Journal*, Mar. 1935.

[B18] Binns, D. F., "Calculation of Field Factor for Vertical Sphere Gap, Taking Account of Surrounding Earthed Surface," *Proceedings of the Institution of Electrical Engineers*, vol. 112, no. 8, pp. 1575–1582, Aug. 1965.

[B19] Binns, D. F. and Hardy, D. R., "Irradiation of Small Sphere-Gaps for Voltage Measurements," *AIEE Transactions. Part I. Communications and Electronics*, vol. 81, no. 60, pp. 155–160, May 1962.

[B20] Blalock, T. J., Bullock, D. F., Zaon, W. S., and Liao, T. W., "Capacitive Voltage Divider for UHV Outdoor Testing," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-89, no. 7, pp. 1404–1412, Sept./Oct. 1970.

[B21] Brady, M. M., Comment on "High-Impulse Current and Voltage Measurement," *IEEE Transactions on Instrumentation and Measurement*, vol. IM-20, no. 1, pp. 79–80, Feb. 1971.

[B22] Broadbant, I. E. and Shlash, A. H. A., "Characteristics and Breakdown Initiation of Triggered Spark Gaps with Uniform Applied Field at Very High Voltages," *Proceedings of the Institution of Electrical Engineers*, vol. 112, no. 11, pp. 2152–2158, Nov. 1965.

[B23] Brown, J. A., "Use of Sulfur Hexafluoride as Gaserous Dielectric," *ASTM Special Technical Publication 346*, pp. 24–34, 1963.

[B24] Bruce, F. M., "Calibration of Uniform-Field Spark Gaps for High-Voltage Measurement at Power Frequencies," *Journal of the Institute of Electrical Engineers* (London), vol. 94, pt. 2, pp. 138–149, Apr. 1947.

[B25] Carroll, J. S. and Cezzens, B., "Sphere-Gap and Point-Gap Arcover Voltage as Determined by Direct Measurements," *AIEE Transactions*, vol. 48, pp. 1–9, Jan. 1929.

[B26] Chubb, L. W. and Fortescue, C., "Calibration of the Sphere Gap Voltmeter," *AIEE Transactions*, vol. 32, pt. 1, pp. 739-748, 1913. Discussion by F. W. Peek, Jr., pp. 812–820.

[B27] Churchill, R. J. and Gallagher, D. F., "Analogue Computer Study of Townsend Gas Discharge," *Journal of Electronics and Control*, vol. 14, no. 6, pp. 599–607, June 1963.

[B28] Clarke, R. H., "Impulse Testing of Power Transformers," *Transactions of the Institution of Engineers —Australia*, vol. EM 4, no. 2, pp. 43–48, Nov. 1962.

[B29] "Corona Resistance of Insulating Materials," *Institute of Electrical Engineers*, Japan, vol. 80, no. 858, pp. 353–384, Mar. 1960.

[B30] Creed, F. C. and Collins, M. M. C., "Shaping Circuits for High Voltage Impulses," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-90, no. 5, pp. 2239–2246, Sept./Oct. 1971.

[B31] Creed, F. C. and Collins, M. M. C., "Transient Impedance of High Voltage Impulse Generating Systems," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-89, no. 7, pp. 1387–1393, Sept./Oct. 1970.

[B32] Dakin, T. W., "Theory of Gas Breakdown," *Progress in Dielectrics*, vol. 4, pp. 151–198, 1962.

[B33] Davis, R. and Bowdler, G. W., "The Calibration of Sphere Gaps with Impulse Voltages," *Journal of the Institute of Electrical Engineers* (London), vol. 82, pp. 645–654, 1938.

[B34] Dehne, K. D., Koehrmann, W., and Lenne, H., "Measurement of Formative Time Lag for Sparks in Air, Hydrogen, and Nitrogen," *Dielectrics*, vol. 2, no. 3, pp. 129–136, Aug. 1963.

[B35] Devins, J. C., and Sharbaugh, A. H., "Fundamental Nature of Electrical Breakdown," *Electrotechnology*, vol. 67, no. 2, pp. 104-122, Feb. 1961 and vol. 68, no. 4, pp. 97–116, Oct. 1961.

[B36] Dutton, J. and Morris, W. T., "Mechanism of Electrical Breakdown of Air in Uniform Fields at Voltages Up to 400 kV," *British Journal of Applied Physics*, vol. 8, pp. 1115–1120, Aug. 1967.

[B37] Edward, F. S. and Smee, J. F., "The Calibration of the Sphere Spark-Gap for Voltage Measurement Up to One Million Volts (Effective at 50 Cycles)," *Journal of the Institute of Electrical Engineers* (London), vol. 82, pp. 655–657, 1938.

[B38] Ely, C. H. A. and Roberts, W. J., "Switching-Impulse Flashover of Air Gaps and Insulators in Artificially Polluted Atmosphere," *Proceedings of the Institution of Electrical Engineers*, vol. 115, no. 11, pp. 1667–1671, Nov. 1968.

[B39] Farnsworth, S. W. and Fortescue, C. L., "The Sphere Spark Gap," *AIEE Transactions*, vol. 32, pt. 1, pp. 733–734, 1913.

[B40] Fryxell, F. and Schei, A., "Influence of High Altitudes on Flashover Voltages of Insulators," *Elteknik*, vol. 9, no. 1, pp. 1–4, Jan. 1966 (in English).

[B41] Govindaraju, G. R. and Badkas, D. J., "Impulse Breakdown of Large Air Gaps in Non-Uniform Electric Fields," *Journal of Scientific and Industrial Research*, vol. 210, no. 9, pp. 308–312, Sept. 1962.

[B42] Guindehi, S., "Influence of Air Humidity Upon the Breakdown Voltage at Different Voltages and Electrode Formations," *Bulletin de l'Association Suisse des Electriciens*, vol. 61, no. 3, pp. 97–104, Feb. 7, 1960 (in French).

[B43] Hagg, W. K. and Walley, C. A., "Assessment of Point-Hemisphere Discharge Gap as Partial Discharge Reference," *Journal of Scientific Instruments*, vol. 43, no. 1, pp. 11–15, Jan. 1966.

[B44] Harada, T., Itami, T., and Aopshima, Y., "Resistor Divider with Dividing Element on High Voltage Side for Impulse Voltage Measurements," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-90, no. 3, pp. 1407–1414, May/June, 1971.

[B45] Harada, T., Kimura, K., Kawamura, T., Aizawa, T., and Akatsee, Y., "Development of a High Quality Resistance Divider for Impulse Voltage Measurements," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-90, no. 5, pp. 2247–2250, Sept./Oct. 1971.

[B46] Hardy, D. R. and Craggs, J. D. "The Irradiation of Spark Gaps for Voltage Measurements," *AIEE Transactions*, vol. 69, pt. 1, pp. 584–590, 1950.

[B47] Hayashi, M. and Ando, N. "Conditions for Spark Discharge and Dielectic Breakdown," *Electrical Engineers in Japan* vol. 86, no. 2, pp. 76–84, Feb. 1966 (translation).

[B48] Heilbronner, F., "Firing of Multistage Impulse Generators," *ETZ* (ed. A), vol. 92, no. 6, pp. 372–376, June 1971.

[B49] Hosokawa, T., Kondo, Y., and Miyoshi, Y., "Prebreakdown Phenomena of Negative Point-to-Plane Air Gap," *Electrical Engineering in Japan*, vol. 89, no. 9, pp. 120–127, Sept. 1969.

[B50] Hubli, S. and Badkas, D. J., "Detection of Corona During Impulse Testing of Transformers," *Indian Journal of Technology*, vol. no. 1, pp. 1–6, Jan. 1963.

[B51] Hylten-Cavallius, N. R. and Vaughn, R. L., "Calibration and Checking Methods of Rapid High-Voltage Impulse Measuring Circuits," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-89, no. 7, pp. 2247–2250, Sept./Oct. 1971.

[B52] IEEE Committee Report, "Switching Surge Tests for Oil-Insulated Power Transformers," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-86, no. 2, pp. 247-249, Feb. 1967; Draft of Proposed Standards, vol. PAS-87, no. 2, pp. 405–407, Feb. 1968.

[B53] "International Conference on Gas Discharge," in *IEE Conference Publication No. 90*, Insitution of Electrical Engineers, p. 405, 1972.

[B54] Ivanov, A. V. and Larinov, V. P., "Effect of Wavefront Steepness and Shape of Electrodes on the Breakdown Voltages in Air Gaps," *Elektrichestvo*, no. 9, pp. 70–73, Sept. 1969 (in Russian).

[B55] Jaskula, H. W., "Control of Impulse Voltage Plant," *AEG Progress*, pp. 274–277, Aug. 2, 1961.

[B56] Jolly, D. C., "Contamination Flashover—1, Theoretical Aspects," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-91, no. 6, pp. 2437–2442, Nov./Dec. 1972.

[B57] Kawai, M., "Research at Project UHV on the Performance of Contaminated Insulators—1, 2," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-92, no. 3, pp. 1102-1120, May/June, 1973.

[B58] Kawai, M. and Milone, D. M., "Tests on Salt-Contaminated Insulators in Artificial and Natural Wet Conditions," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-88, no. 9, pp. 1394–1399, Sept. 1969.

[B59] Kuffel, E. and Abdullah, M., "Corona and Breakdown Voltage Characteristics in Sphere-Plane and Rod-Rod Gaps Under Impulse Voltages of Various Wavefront Durations," *Proceedings of the Institution of Electrical Engineers*, vol. 113, no. 6, pp. 1113–1119, June 1966.

[B60] Kurtz, M., "Comparison of Tracking Test Methods," *IEEE Transactions on Electrical Insulation*, vol. EI-6, no. 2, pp. 76–81, June 1971.

[B61] LaCoste, R., Guyeland, A., and Galand, J., "Study of the Phenomenon of Partial Discharge," *Revue General de l'Electricite*, vol. 80, no. 3, pp. 119–235, Mar. 1971 (in French).

[B62] Lambeth, P. J., and Schneider, H. M., "Final Report on the Clean Fog Test for HVAC Insulators," *IEEE Transactions on Power Delivery*, vol. PWRD-2, no. 4, pp. 1317–326, Oct. 1987.

[B63] Mandelcorn, L. and Sommerman, G. M. L., "Tracking and Arc Resistance of Materials," in *Electric Insulation Conference, Materials and Application*, 5th Technical Paper, 1963, pp. 91–93.

[B64] Mason, J. H., "Dielectric Breakdown by Discharges," *Electrotechniek*, vol. 40, no. 3, pp. 48–55, Feb. 1962.

[B65] Meador, J. R., "Calibration of the Sphere Gap," *AIEE Transactions*, vol. 53, pp. 942–948, June 1934; Discussions, pp. 1652-1600, Dec. 1934.

[B66] Meek, C. M., "The Influence of Irradiation on the Measurement of Impulse Voltages with Sphere Gaps," *Journal of the Institute of Electrical Engineers* (London), vol. 93, pt. 2, pp. 97–115, 1946.

[B67] Meek, J. M., "The Electric Spark in Air," *Journal of the Institute of Electrical Engineers* (London), vol. 89, p. 235, 1942.

[B68] Menemenlis, C. and Isaksson, K., "Front Shape of Switching Impulses and Its Effect on Breakdown Parameters," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-93, no. 5, pp. 1380–1389, Sept./Oct. 1974.

[B69] Miyoshi, Y., "Development of Space Charge and Growth of Ionization in Transient Townsend Discharge," *Physics Revue*, vol. 117, no. 2, pp. 335–365, Jan. 1960.

[B70] Moore, H. R., "Re-Examination of the Actual Recommendations for High-Voltage Testing of Transformers," *CIGRE, International Conference on Large High Voltage Electric Systems*, 25th Session, Paris, France, Aug. 21–29, 1974, Paper No. 12-04.

[B71] Mulcahey, M. J., Midde, H., and Bell, W. R., "Insulation, Breakdown, and Switching in High Pressure Gases," in *Proceedings of the Eighth Electrical Insulation Conference*, paper No. IEEE 68C6-EI-92, Dec. 9–12, 1968, pp. 221-226.

[B72] Naito, K., and Schneider, H. M., "Round-Robin Artificial Contamination Test on High Voltage C Insulators," presented at the IEEE/PES 1994 Summer Meeting—San Francisco, CA, Paper 94 SM 462-2 PWRD, July 1994.

[B73] Nemeth, E. and Csaki, E., "Methods of Mathematical Statistics for Evaluating Electric Breakdown Measuring Series," *Periodica Polytechnica Electrical Engineering*, vol. 7, no. 1, pp. 9–35, 1963.

[B74] Nord, G.L., "Effect of Ultraviolet on Breakdown Voltage," *AIEE Transactions*, vol. 54, pp. 955–958, Sept. 1935; Discussions, vol. 55, pp. 272–274, Mar. 1935.

[B75] Olyphant, M. Jr., "Corona and Treeing Breakdown of Insulation—Progress and Problems," *Insulation* (Libertyville, IL), vol. 9, no. 2, pp. 35-40, Feb. 1963; vol. 9, no. 3, pp. 23–27; Mar. 1963, vol. 9, no. 4, pp. 42-46, Apr. 1963.

[B76] Park, J. H. and Cones, H. N., "Spark-Gap Flashover Measurements for Steeply Rising Voltage Impulses," *Journal of Research of the National Bureau of Standards, Section C (Engineering and Instrumentation)*, vol. 66c, no. 3, pp. 197–207, July/Sept. 1962.

[B77] Parnell, T. M., "Transient Overvoltage in Power Frequency Flashover Tests," *Institution of Engineers—Australia—Transactions on Electrical and Mechanical Engineering*, vol. EM 6, no. 1, pp. 1–6, May 1964.

[B78] Parnell, T. M., "Triggered Chopping Gap for Use in Transformers and for Tertiary Windings," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-88, no. 8, pp. 1183-1186, Aug. 1969.

[B79] Pederson, A. and Lausen, P., "Dynamic Properties of Impulse Measuring Systems," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-90, no. 3, pp. 1424-1432, May/June 1971.

[B80] Peek, F. W. Jr., "The Sphere Gap as a Means of Measuring High Voltage," *AIEE Transactions*, vol. 33, pt. 1, pp. 923–949, 1914.

[B81] Penny, G. W., "Photoionization and Breakdown," *National Research Council Publication 1080*, pp. 57–59, 1963.

[B82] Petersen, A., "Calculation of Spark Breakdown or Corona Starting Voltages in Non-Uniform Fields," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-86, no. 2, pp. 200–206, Feb. 1967.

[B83] Poland, M. G., Scarborough, W. E., Hill, H. L., and Renner, P. E., "BPA's Extra High Voltage DC Tests," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-86, no. 10, pp. 1146–60, Oct. 1967.

[B84] Prabhakar, B. R., Nandagopal, M. R., and Gopalakreskhna, H. V., "Effect of Humidity and Temperature of Impulse Flashover Voltage of Air Gaps," *Proceedings of the Institution of Electrical Engineers*, vol. 118, no. 6, pp. 823–824, June 1971.

[B85] Prasad, A. N. and Braggs, J. D., "Measurement of Ionization and Attachment Coefficients in Humid Air in Uniform Fields and Mechanism of Breakdown," *Proceedings of the Physics Society*, vol. 76, no. 488, pp. 223–232, Aug. 1960.

[B86] Rasquin, W., "Effect of Prebreakdown Stresses on Breakdown Impulse Voltages of Electrode Arrangements in Air," *ETZ*, vol. 90, no. 17, pp. 415–420, Aug. 15, 1969 (in German).

[B87] Sprague, C. S. and Gold, G., "Sixty-Cycle Calibration of the 50-Centimeter Sphere Gap," *AIEE Transactions*, vol. 57, pp. 45–59, Jan. 1938.

[B88] "Standard Methods of Test for Dielectric Breakdown Voltage and Dielectric Strength of Insulating Materials at Commercial Power Frequencies," pp. 13–21, *1965 Book of ASTM Standards*, Part 27.

[B89] Suzuki, T., "Breakdown Phenomena in Point-to-Point Gaps," in *IEEE Industry Applications Society 9th Annual Meeting Conference Record*, pp. 371-386, Oct. 7–10, 1974.

[B90] Takeshita, H., Miyake, Y., Oikawa, T., and Kamata, Y., "Flashover Characteristics of Large Gap Spacings in Air," *Hitachi Review*, vol. 11, no. 5, pp. 19–28, Dec. 1962.

[B91] Tomas, R. J., "High-Impulse Current and Voltage Measurement," *IEEE Transactions on Instrumentation and Measurement*, vol. IM-19, no. 2, pp. 102–117, May 1970 (a survey of methods).

[B92] Train, D. and Trinh, G., "Prevention of Recovery Overvoltages on High Voltage Testing Transformers," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-90, no. 5, pp. 1631–1641, Sept./Oct. 1973.

[B93] Train, D. and Vohl, P. E., "Determination of Ratio Characteristics of Cascade Connected Transformers," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-95, no. 6, pp. 1911–1928, Nov./Dec. 1976.

[B94] Train, D., and Dube, R., "Measurements of Voltage Distribution on Suspension Insulators for HVDC Transmission Lines," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-102, no. 8, pp. 2461–2475, Aug. 1983.

[B95] Udo, T., "Sparkover Characteristics of Large Gap Spaces and Long Insulator Strings," *IEEE Transactions on Power Apparatus and Systems*, vol. 83, no. 5, pp. 471–483, May 1964.

[B96] Udo, T. and Tada, T., "Long Tail Surge Flashover Characteristics of Air Gaps and Insulator Strings," *Electrical Engineering in Japan*, vol. 83, no. 9, pp. 39–45, Sept. 1963 (English translation of *Denki Gakkai Zasshie*).

[B97] Udo, T., Tada, T., and Watanabe, Y., "Flashover Characteristics of Large Gap Spacings Due to Pulse and Switching Surges," *Electrical Engineering in Japan*, vol. 84, no. 12, pp. 69–78, Dec. 1964 (translation).

[B98] Udo, T. and Watanabe, Y., "DC High-Voltage Sparkover Characteristics of Gaps and Insulator Strings," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-87, no. 1, pp. 266–270, Jan. 1968.

[B99] Vlastos, A. E., "Breakdown of Air in Non-Homogeneous Fields," *Proceedings of the Institution of Electrical Engineers*, vol. 113, no. 5, pp. 921–930, May 1966.

[B100] Vorozhtsov, B. I., "Measurement of Dielectric Properties of Insulating Materials," *Instruments and Experimental Techniques*, no. 2, pp. 115–118, Jan./Feb. 1959 (translation of *Pribory i Tekhnika Eksperimenta*).

[B101] Wada, W., "Switching Surge Flashover Characteristics of Point-Electrode Gaps," *Electrical Engineering in Japan*, vol. 89, no. 8, pp. 62–68, Aug. 1969.

[B102] Wagner, C. F., "Determination of the Wave Front of Lighting Stroke Currents from Field Measurements," *AIEE Transactions. Part III. Power Apparatus and Systems*, vol. 79, no. 50, pp. 581–589, Oct. 1960.

[B103] Wagner, C. F. and Hileman, A. R., "Mechanism of Breakdown of Laboratory Gaps," *AIEE Transactions. Part III. Power Apparatus and Systems*, vol. 80, no. 56, pp. 604–622, Oct. 1961.

[B104] Ward, A. L., "Understanding Electrical Breakdown in Gases," *National Research Council Publication 973*, pp. 91-94, 1962.

[B105] Watanabe, Y., "Switching Surge Flashover Characteristics of Extremely Long Air Gaps," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-86, no. 8, pp. 933–936, Aug. 1967.

[B106] Waters, R. T. and Jones, R. E., "Impulse Breakdown Voltage and Time-Lag Characteristics of Long Gaps in Air," *Royal Society of London—Philosophical Transactions*, vol. 256, no. 1069, pp. 185–234, Apr. 9, 1964.

[B107] Waters, R. T., Rickard, T. E. S., and Stark, W. B., "Electric Field and Current Density in Impulse Corona Discharge in Rod-Plane Gap," *Proceedings of the Royal Society of London*, vol. 304, no. 1477, pp. 187–210, Apr. 16, 1968.

[B108] Whitehead, S. A., "A Note on Standard Calibration for Sphere Gaps," *Journal for the Institute of Electrical Engineers* (London), vol. 84, pp. 408–416, 1939.

[B109] Williams, T. J., "Theory and Design of Triggered Spark Gaps," U.S. Department of Commerce—Office of Technical Services, SCTM 186–59 (14), pp. 180, May 1959.

[B110] Zaengl, W., "Determination of the Complete Transmission Properties of an Impulse Voltage Measuring Circuit," *ETZ*, vol. 90, no. 19, pp. 457–462, Sept. 12, 1969.