

IEEE Standard Techniques for High-Voltage Testing

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**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 voltages, 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

The Institute of Electrical and Electronics Engineers, Inc.
345 East 47th Street, New York, NY 10017-2394, USA

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ISBN 1-55937-532-9

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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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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.

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

²IEEE 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.

³Information 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:

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

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

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

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.

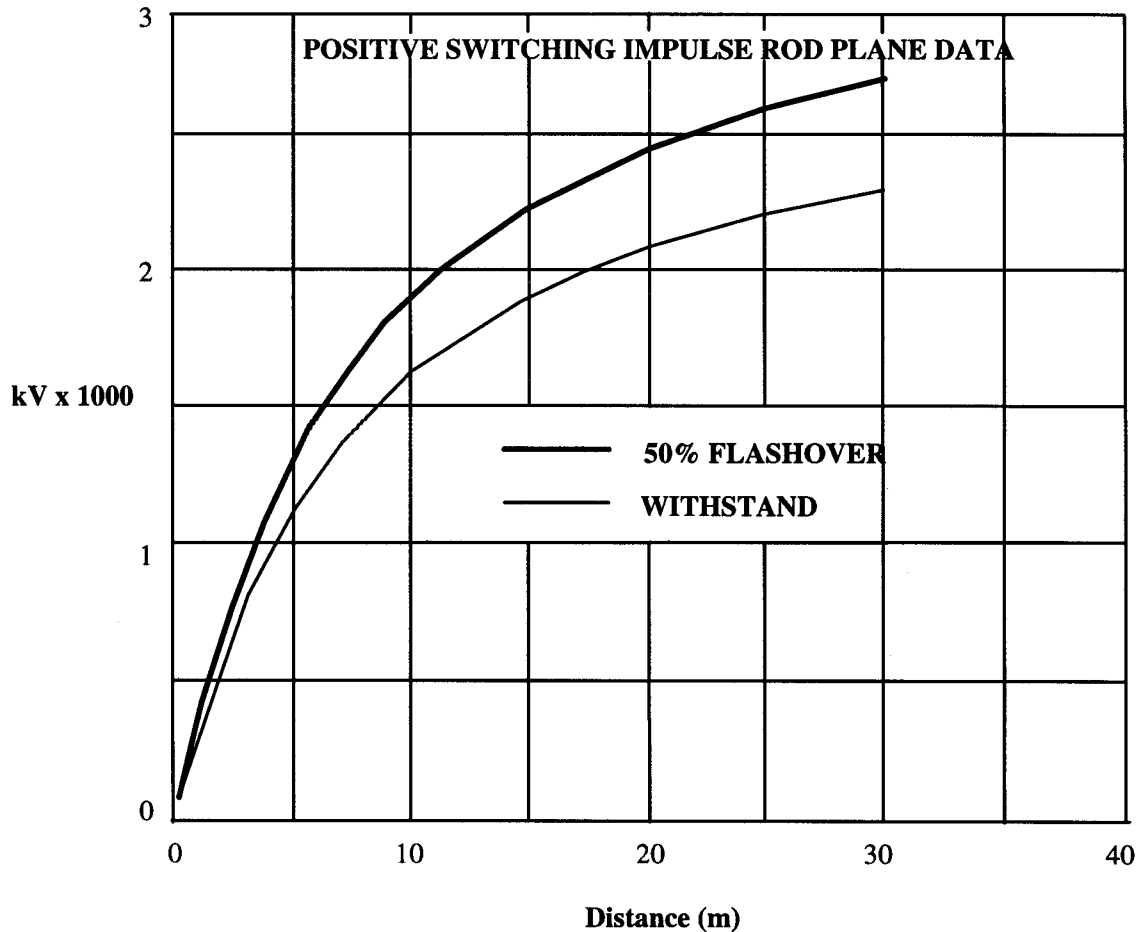


Figure 1 – Voltage versus distance for rod-plane gap

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 spark-over.

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 sys-

tem 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)

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

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:

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

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 over-voltage 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 $\pm 5\%$.

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 k Ω , 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 dur-

ing 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 over-voltages 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

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

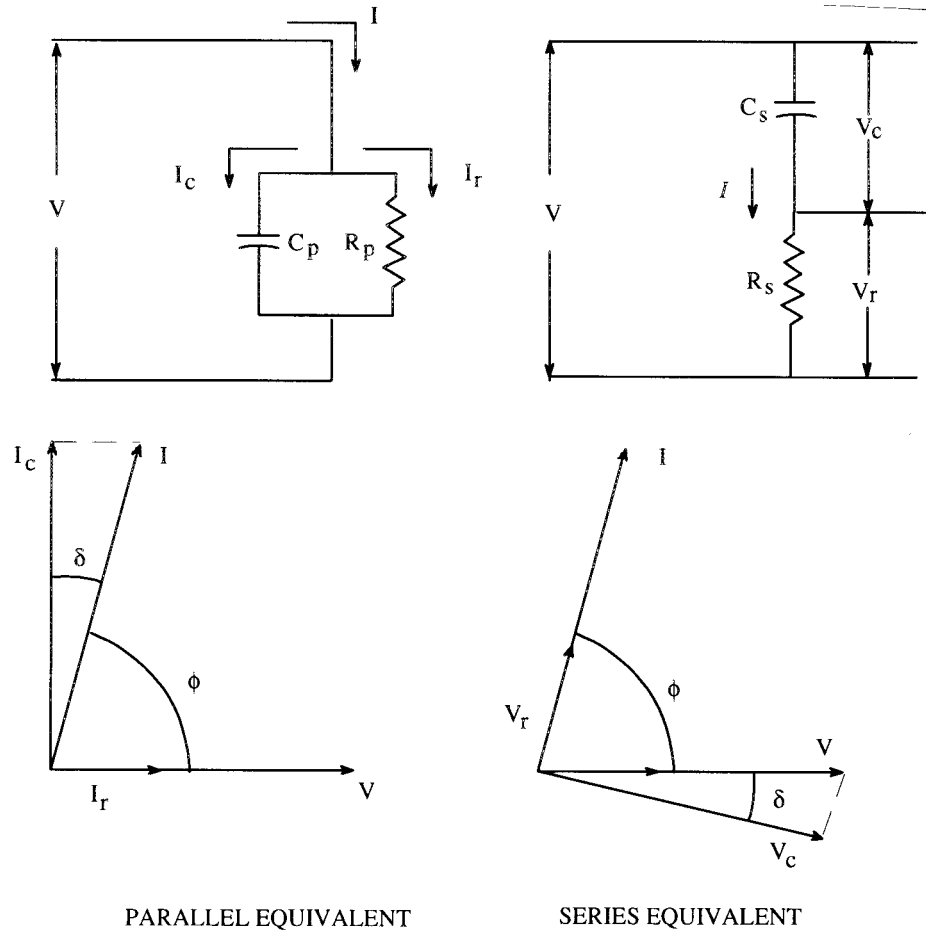
$$\text{Power factor (or cosine } \phi) = \frac{I_r}{I} = \frac{1}{\sqrt{1 + \omega^2 R_p^2 C_p^2}} \quad (7)$$

- b) Series equivalent circuit

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

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

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:

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

where

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

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

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

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

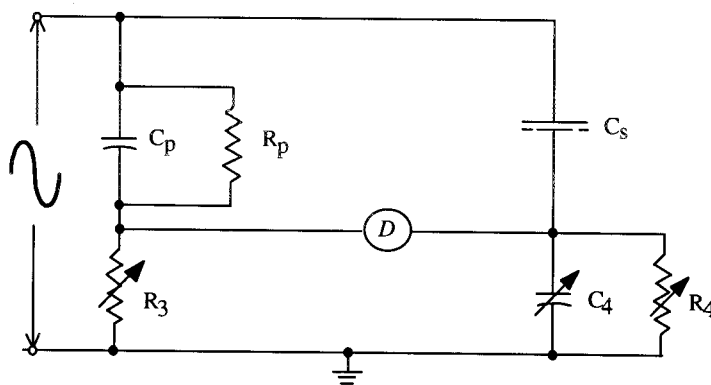
$$R_p = R_3 \left(\frac{C_4}{C_s} \right) \quad C_p = C_s \left(\frac{R_4}{R_3} \right) \quad (14)$$

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

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



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

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

where

R_2 is a variable resistor in the bridge

C_2 is a capacitor in the bridge

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

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

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

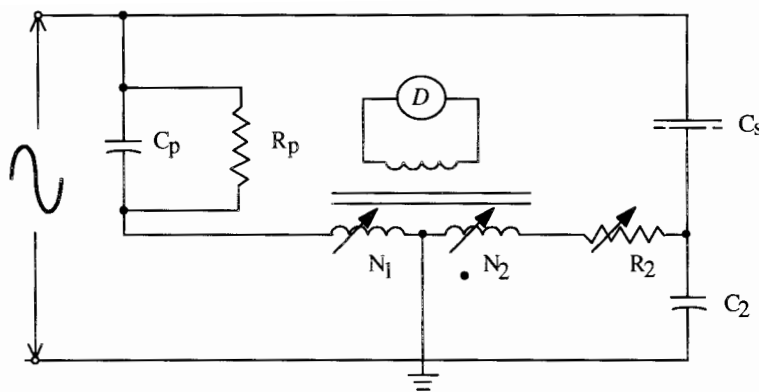


Figure 4—Measurement method—transformer ratio arm bridge basic circuit

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 $\tan \delta$ because the maximum power factor can never exceed 1, whereas the maximum value of $\tan \delta$ 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 ($\tan \delta_1$) are measured. The test object is then connected to the high-voltage supply and the new capacitance (C_2) and dissipation factors ($\tan \delta_2$) are measured. The capacitance of the test object (C_x) is determined from

$$C_x = C_2 - C_1 \quad (18)$$

and

$$\tan \delta = \frac{C_2 \tan \delta_2 - C_1 \tan \delta_1}{C_2 - C_1} \quad (19)$$

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 μ s, the peak value is taken as the maximum value of the recorded trace. If the oscillation fre-

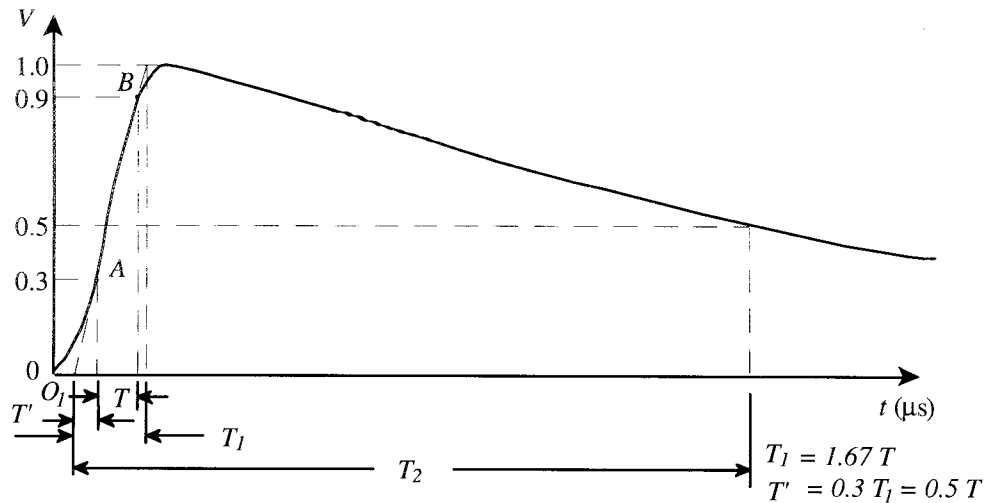


Figure 5—Full lightning impulse without oscillations or overshoots

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)

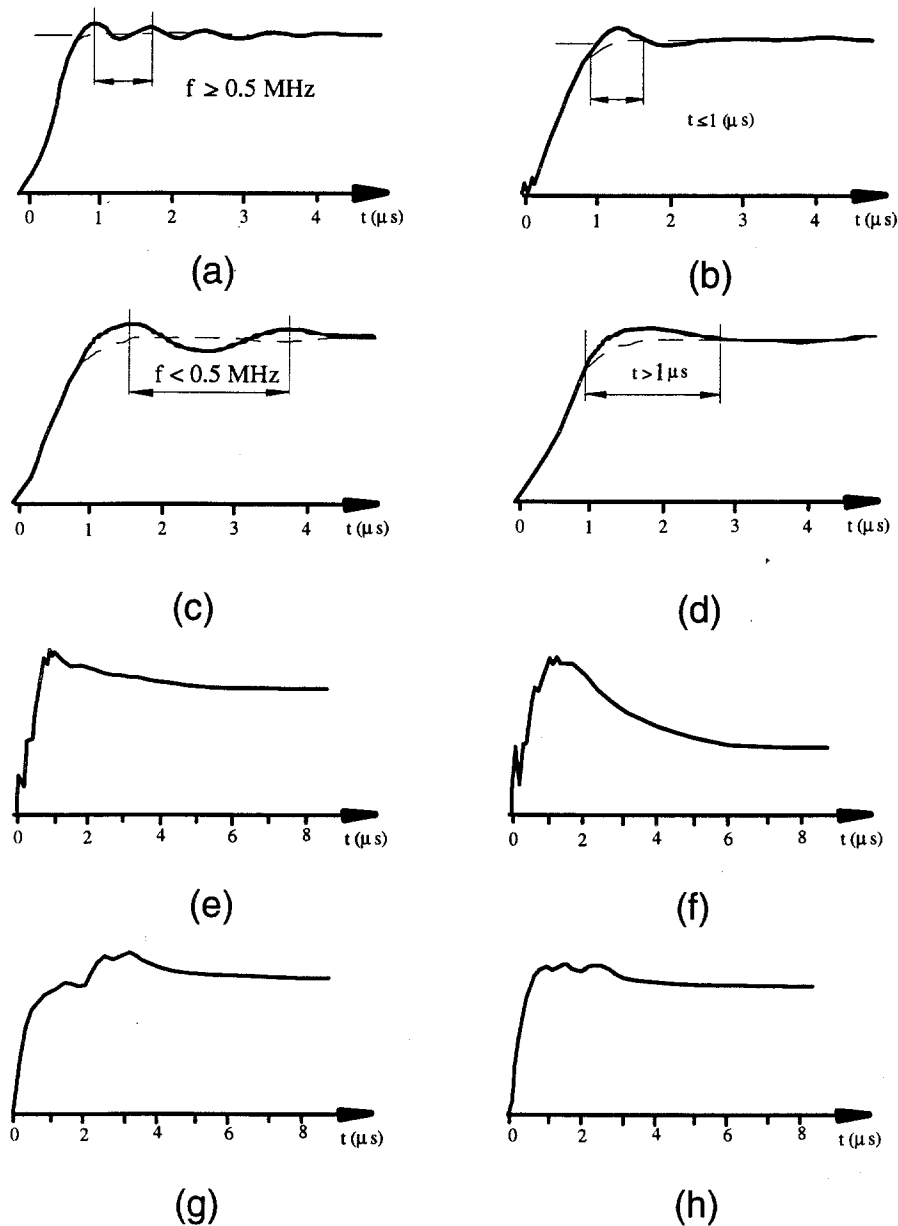
The virtual origin (O_1) of a lightning impulse is the instant preceding that corresponding to point A in figure 5 by a time $0.3 T_1$. This is the intersection with the time axis of a straight line drawn through reference points A and B on the front.

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.

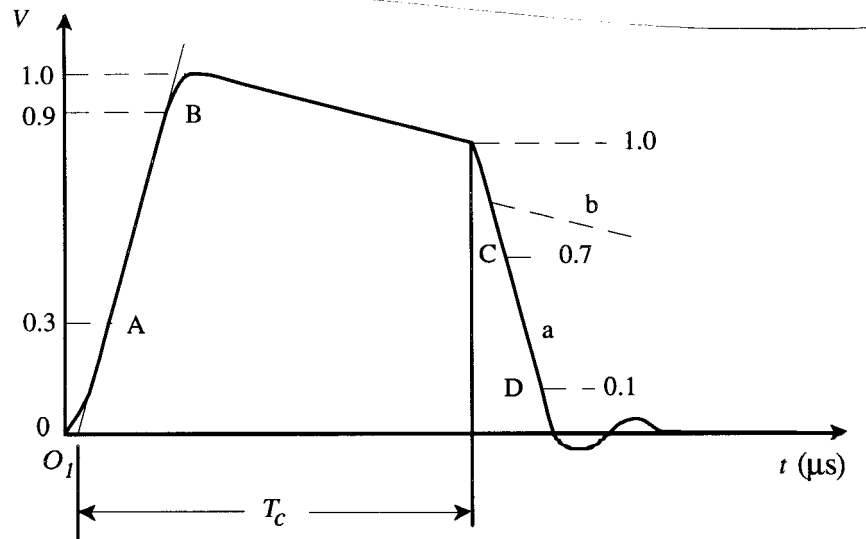
For figures e), f), g), and h)—No general guidance can be given for the determination of the value of the test voltage.

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

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

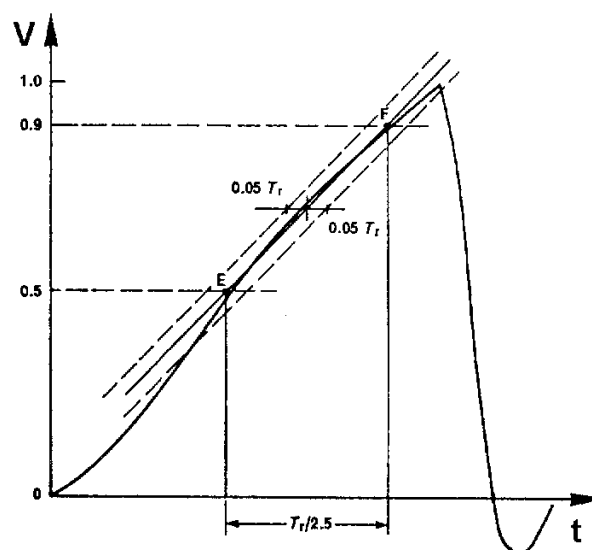


Figure 8—Linearly rising front-chopped impulse

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.

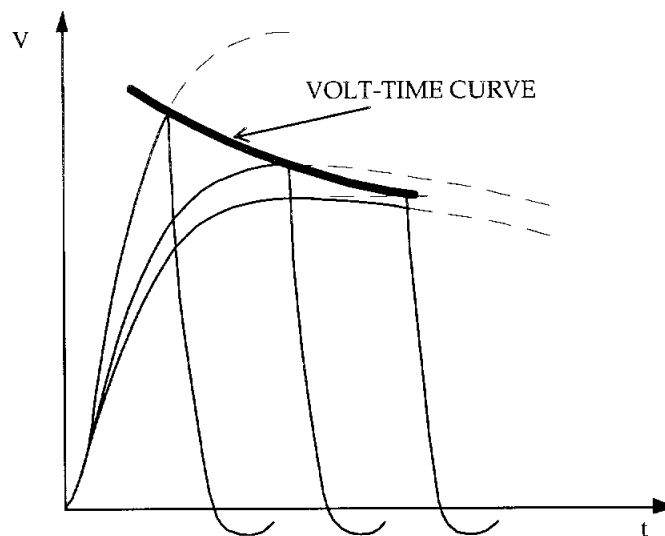


Figure 9— Voltage/time curve for impulses of constant prospective shape

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 $\pm 3\%$
- b) Virtual front time $\pm 30\%$
- c) Virtual time to half-value $\pm 20\%$

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 μ s, 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

$$f_{\max} = \frac{75}{2H} \quad (20)$$

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

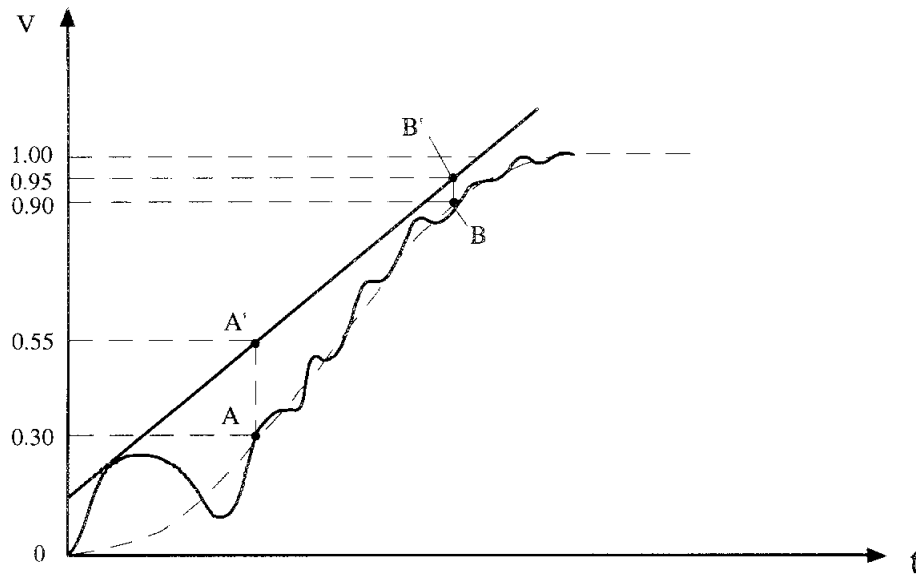


Figure 10—Maximum permissible amplitude of oscillations on the wavefront

should be checked for each test object. Where a number of test objects of identical design and size are tested under identical conditions, the shape need only be verified once if only the withstand voltage is of interest.

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

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

- The required accuracy of test results
- The random nature of the observed phenomenon and any polarity dependence of the measured characteristic
- 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

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

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

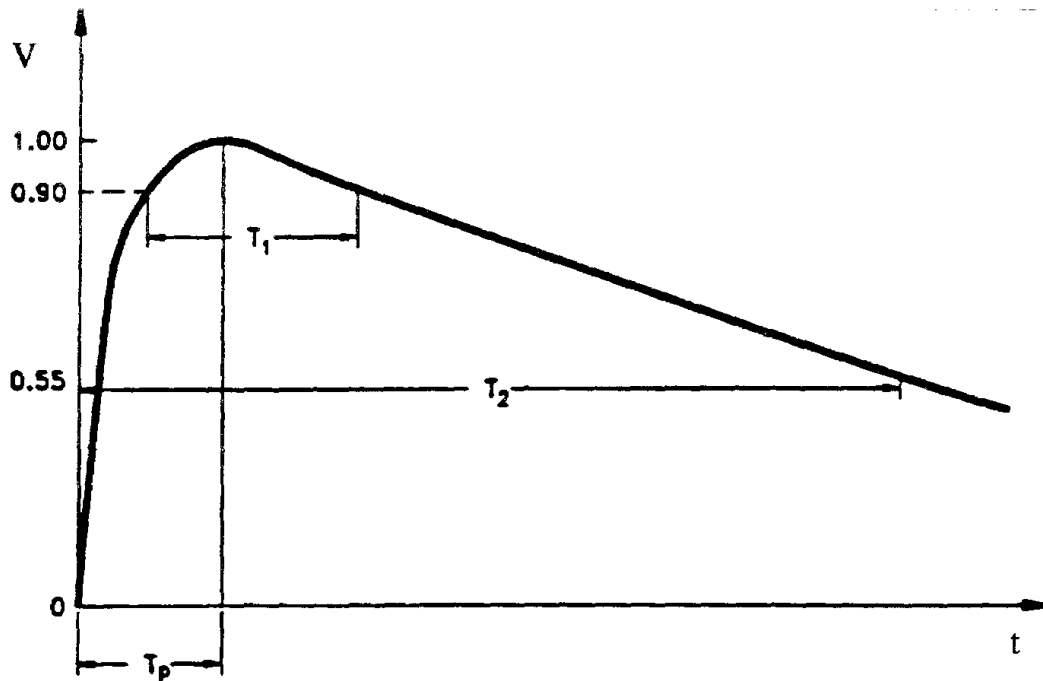


Figure 11—Full switching impulse

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

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

$$K = 2.42 - 3.08E-03(T_x) + 1.51E-04(T_2) \quad (23)$$

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 | $\pm 3\%$ |
| b) | Time to peak | $\pm 20\%$ |
| c) | Time to half-value | $\pm 60\%$ |

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 lightning 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)].

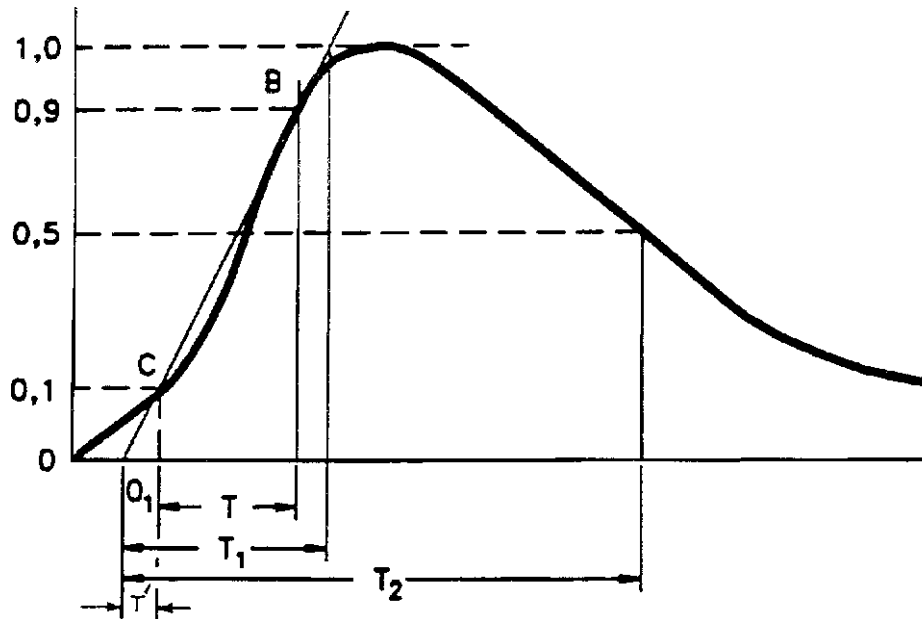


Figure 12—Exponential impulse current

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:

- The 4/10 impulse with virtual front time of $4 \mu\text{s}$ and time of half-value of $10 \mu\text{s}$
- The 8/20 impulse with virtual front time of $8 \mu\text{s}$ and time to half-value of $20 \mu\text{s}$
- Rectangular impulse currents with durations of the peak of $500 \mu\text{s}$, $1000 \mu\text{s}$, or $2000 \mu\text{s}$ and total durations from $2000 \mu\text{s}$ to $3200 \mu\text{s}$.

Other shapes may be defined by the appropriate apparatus standard.

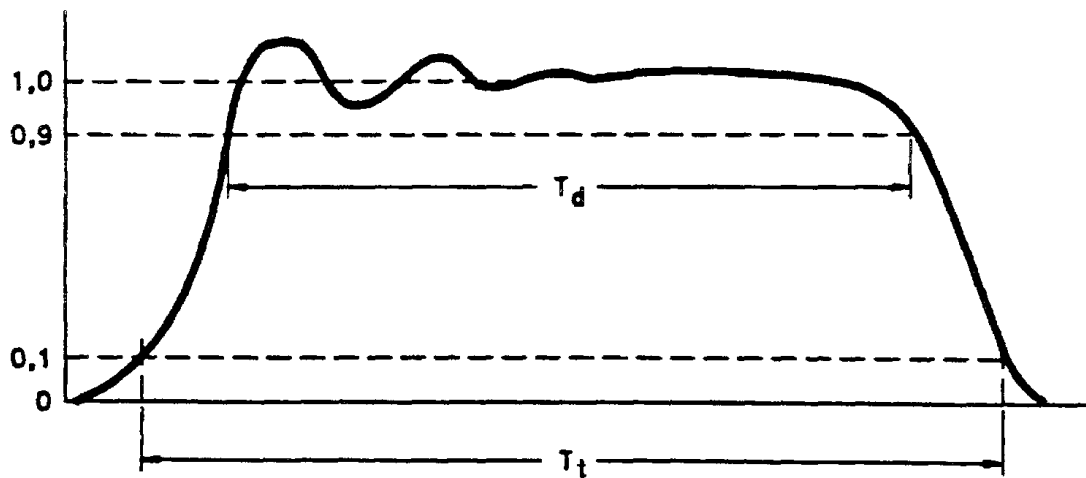


Figure 13—Rectangular impulse current

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 $\pm 10\%$
- b) Virtual front time (T_1) $\pm 10\%$
- c) Virtual time to half-value (T_2) $\pm 10\%$

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.

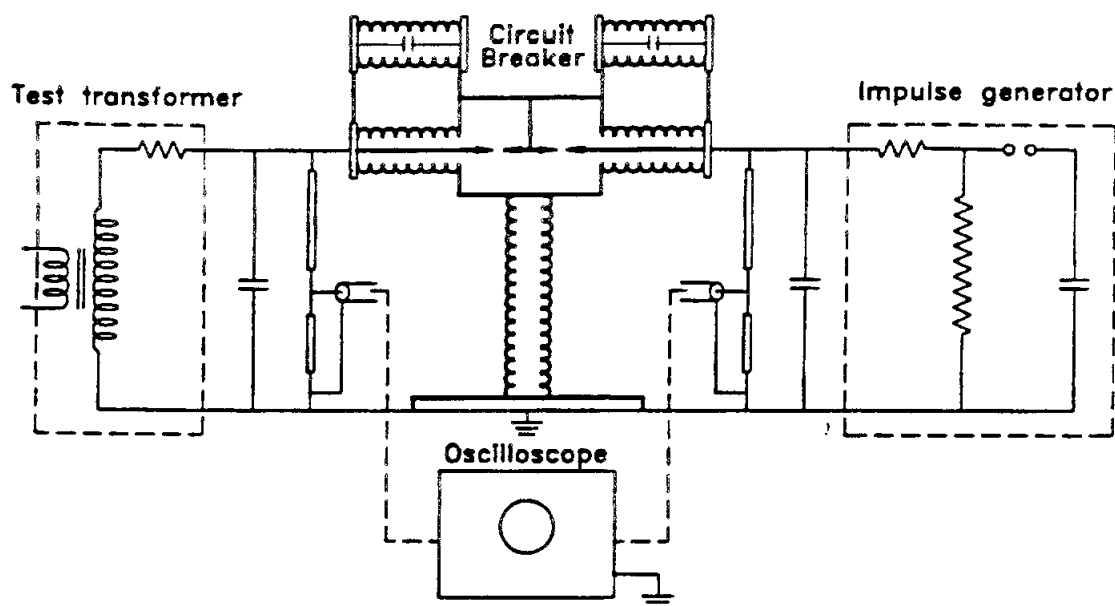


Figure 14—Typical test circuit for combined tests