BS EN 60060-1:2010

BSI Standards Publication

High-voltage test techniques

Part 1: General definitions and test requirements

...making excellence a habit.™

National foreword

This British Standard is the UK implementation of EN 60060-1:2010. It is identical to IEC 60060-1:2010. It supersedes BS 923-1:1990, which is withdrawn.

The UK participation in its preparation was entrusted to Technical Committee PEL/42, Testing techniques for high voltages and currents.

A list of organizations represented on this committee can be obtained on request to its secretary.

ISBN 978 0 580 68953 6

ICS 17.220.20; 19.080

This British Standard was published under the authority of the Standards Policy and Strategy Committee on 28 February 2011.

Amendments issued since publication

Amd. No.	Date	Text affected

EUROPEAN STANDARD
NORME EUROPÉENNE
EUROPÄISCHE NORM

EN 60060-1

December 2010

ICS 17.220.20

Supersedes HD 588.1 S1:1991

English version

High-voltage test techniques - Part 1: General definitions and test requirements
(IEC 60060-1:2010)

Technique des essais à haute tension -
Partie 1: Définitions et exigences
générales
(CEI 60060-1:2010)

Hochspannungs-Prüftechnik -
Teil 1: Allgemeine Begriffe und
Prüfbedingungen
(IEC 60060-1:2010)

This European Standard was approved by CENELEC on 2010-12-01. CENELEC members are bound to comply with the CEN/CENELEC Internal Regulations which stipulate the conditions for giving this European Standard the status of a national standard without any alteration.

Up-to-date lists and bibliographical references concerning such national standards may be obtained on application to the Central Secretariat or to any CENELEC member.

This European Standard exists in three official versions (English, French, German). A version in any other language made by translation under the responsibility of a CENELEC member into its own language and notified to the Central Secretariat has the same status as the official versions.

CENELEC members are the national electrotechnical committees of Austria, Belgium, Bulgaria, Croatia, Cyprus, the Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, the Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, Switzerland and the United Kingdom.

CENELEC
European Committee for Electrotechnical Standardization
Comité Européen de Normalisation Electrotechnique
Europäisches Komitee für Elektrotechnische Normung

Management Centre: Avenue Marnix 17, B - 1000 Brussels

Foreword

The text of document 42/277/FDIS, future edition 3 of IEC 60060-1, prepared by IEC/TC 42, High-voltage testing techniques, was submitted to the IEC-CENELEC parallel vote and was approved by CENELEC as EN 60060-1 on 2010-12-01.

This European Standard supersedes HD 588.1 S1:1991.

This EN 60060-1:2010 includes the following technical changes with respect to HD 588.1 S1:1991:

– The general layout and text was updated and improved to make the standard easier to use.

– Artificial pollution test procedures were removed as they are now described in EN 60507.

– Measurement of impulse current has been transferred to a new standard on current measurement (EN 62475).

– The atmospheric correction factors are now presented as formulas.

– A new method has been introduced for the calculation of the time parameters of lightning impulse waveforms. This improves the measurement of the time parameters of lightning impulses with oscillations or overshoot.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. CEN and CENELEC shall not be held responsible for identifying any or all such patent rights.

The following dates were fixed:

– latest date by which the EN has to be implemented at national level by publication of an identical national standard or by endorsement	(dop)	2011-09-01
– latest date by which the national standards conflicting with the EN have to be withdrawn	(dow)	2013-12-01

Annex ZA has been added by CENELEC.

Endorsement notice

The text of the International Standard IEC 60060-1:2010 was approved by CENELEC as a European Standard without any modification.

Annex ZA
(normative)

Normative references to international publications with their corresponding European publications

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

NOTE When an international publication has been modified by common modifications, indicated by (mod), the relevant EN/HD applies.

Publication	Year	Title	EN/HD	Year
IEC 60060-2	-	High-voltage test techniques - Part 2: Measuring systems	EN 60060-2	-
IEC 60270	-	High-voltage test techniques - Partial discharge measurements	EN 60270	-
IEC 60507	1991	Artificial pollution tests on high-voltage insulators to be used on a.c. systems	EN 60507	1993
IEC 61083-1	-	Instruments and software used for measurement in high-voltage impulse tests - Part 1: Requirements for instruments	EN 61083-1	-
IEC 61083-2	-	Digital recorders for measurements in high-voltage impulse tests - Part 2: Evaluation of software used for the determination of the parameters of impulse waveforms	EN 61083-2	-
IEC 62475	-	High-current test techniques - Definitions and requirements for test currents and measuring systems	EN 62475	-

CONTENTS

HIGH-VOLTAGE TEST TECHNIQUES –

Part 1: General definitions and test requirements

1 Scope

This part of IEC 60060 is applicable to:

- dielectric tests with direct voltage;
- dielectric tests with alternating voltage;
- dielectric tests with impulse voltage;
- dielectric tests with combinations of the above.

This part is applicable to tests on equipment having its highest voltage for equipment U_m above 1 kV.

NOTE 1 Alternative test procedures may be required to obtain reproducible and significant results. The choice of a suitable test procedure should be made by the relevant Technical Committee.

NOTE 2 For voltages U_m above 800 kV meeting some specified procedures, tolerances and uncertainties may not be achievable.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60060-2, *High-voltage test techniques – Part 2: Measuring systems*

IEC 60270, *High-voltage test techniques – Partial discharge measurements*

IEC 60507:1991, *Artificial pollution tests on high-voltage insulators to be used on a.c. systems*

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

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

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

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

3.1 Definitions related to characteristics of discharges

3.1.1
disruptive discharge
failure of insulation under electric stress, in which the discharge completely bridges the insulation under test, reducing the voltage between electrodes to practically zero

NOTE 1 Non-sustained disruptive discharge in which the test object is momentarily bridged by a spark or arc may occur. 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 allow the test voltage to reach a higher value. Such an event should be interpreted as a disruptive discharge unless otherwise specified by the relevant Technical Committee.

NOTE 2 A disruptive discharge in a solid dielectric produces permanent loss of dielectric strength; in a liquid or gaseous dielectric the loss may be only temporary.

3.1.2
sparkover
disruptive discharge that occurs in a gaseous or liquid dielectric

3.1.3
flashover
disruptive discharge that occurs over the surface of a dielectric in a gaseous or liquid dielectric

3.1.4
puncture
disruptive discharge that occurs through a solid dielectric

3.1.5
disruptive-discharge voltage value of a test object
value of the test voltage causing disruptive discharge, as specified, for the various tests, in the relevant clauses of the present standard

3.1.6
non-disruptive discharge
discharge between intermediate electrodes or conductors where the test voltage does not collapse to zero

NOTE 1 Such an event should not be interpreted as a disruptive discharge unless so specified by the relevant Technical Committee.

NOTE 2 Some non-disruptive discharges are termed “partial discharges” and are dealt with in IEC 60270.

3.2 Definitions relating to characteristics of the test voltage

3.2.1
prospective characteristics of a test voltage
characteristics which would have been obtained if no disruptive discharge had occurred. When a prospective characteristic is used, this shall always be stated.

3.2.2
actual characteristics of a test voltage
those characteristics which occur during the test at the terminals of the test object

3.2.3
value of the test voltage
as defined in the relevant clauses of this standard

3.2.4
withstand voltage of a test object
specified prospective voltage value which characterizes the insulation of the object with regard to a withstand test

NOTE 1 Unless otherwise specified, withstand voltages are referred to standard reference atmospheric conditions (see 4.3.1).

NOTE 2 This applies to external insulation only.

3.2.5
assured disruptive-discharge voltage of a test object
specified prospective voltage value which characterizes its performance with regard to a disruptive-discharge test

3.3 Definitions relating to tolerance and uncertainty

3.3.1
tolerance
constitutes the permitted difference between the measured value and the specified value

NOTE 1 This difference should be distinguished from the uncertainty of a measurement.

NOTE 2 A pass/fail decision is based on the measured value, without consideration of the measurement uncertainty.

3.3.2
uncertainty (of measurement)
parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could be reasonably attributed to the measurand

[IEV 311-01-02]

NOTE 1 In this standard, all uncertainty values are specified at a level of confidence of 95 %.

NOTE 2 Uncertainty is positive and given without sign.

NOTE 3 It should not be confused with the tolerance of a test-specified value or parameter.

3.4 Definitions relating to statistical characteristics of disruptive-discharge voltage values

3.4.1
disruptive-discharge probability of a test object
p
probability that one application of a certain prospective voltage value of a given shape will cause disruptive discharge in the test object

NOTE The parameter p may be expressed as a percentage or a proper fraction.

3.4.2
withstand probability of a test object
q
probability that an application of a certain prospective voltage value of a given shape does not cause a disruptive discharge on the test object

NOTE If the disruptive-discharge probability is p, the withstand probability q is $(1 - p)$.

3.4.3
p % disruptive-discharge voltage of a test object
U_p
prospective voltage value which has p % probability of producing a disruptive discharge on the test object

NOTE 1 Mathematically the p % disruptive-discharge voltage is the quantile of the order p (or p quantile) of the breakdown voltage.

NOTE 2 U_{10} is called the “statistical withstand voltage” and U_{90} is called the “statistical assured disruptive-discharge voltage”.

3.4.4
50 % disruptive-discharge voltage of a test object

U_{50}

prospective voltage value which has a 50 % probability of producing a disruptive discharge on the test object

3.4.5
arithmetic mean value of the disruptive-discharge voltage of a test object,

U_a

$$U_a = \frac{1}{n}\sum_{i=1}^{n} U_i$$

where

U_i is the measured disruptive-discharge voltage and

n is the number of observations (discharges).

NOTE For symmetric distributions U_a is identical to U_{50}.

3.4.6
standard deviation of the disruptive voltage of a test object

s

a measure of the dispersion of the disruptive voltage estimated by

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

where

U_i is the i^{th} measured disruptive voltage and

U_a is the arithmetic mean of the disruptive voltages (in most cases it is identical to U_{50}).

n is the number of observations (discharges).

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

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

3.5 Definitions relating to classification of insulation in test objects

3.5.1
external insulation

air insulation and the exposed surfaces of solid insulation of the equipment, which are subject both to dielectric stresses and to the direct effects of atmospheric and other external conditions

3.5.2
internal insulation

internal solid, liquid or gaseous elements of the insulation of equipment protected from the direct effects of external conditions such as pollution, humidity and vermin

3.5.3
self-restoring insulation
insulation which completely recovers its insulating properties after a disruptive discharge caused by the application of a test voltage

[IEV 604-03-04, modified]

3.5.4
non-self-restoring insulation
insulation which loses its insulating properties, or does not recover them completely, after a disruptive discharge caused by the application of a test voltage

[IEV 604-03-05, modified]

NOTE In high-voltage apparatus, parts of both self-restoring and non-self-restoring insulation are always operating in combination and some parts may be degraded by repeated or continued voltage applications. The behaviour of the insulation in this respect should be taken into account by the relevant Technical Committee when specifying the test procedures to be applied.

4 General requirements

4.1 General requirements for test procedures

The test procedures applicable to particular types of test objects, for example, the test voltage, the polarity to be used, the preferred order if both polarities are to be used, the number of applications and the interval between applications shall be specified by the relevant Technical Committee, having regard to such factors as:

- the required accuracy of the test results;
- the random nature of the observed phenomena;
- any polarity dependence of the measured characteristics and
- the possibility of progressive deterioration with repeated voltage applications.

At the time of a test, the test object shall be complete in all essential details, and it should have been processed in the normal manner for similar equipment.

At the time of a test, the test object should have become acclimatised as much as practicable to the ambient atmospheric conditions of the test area. The period allocated to reach equilibrium should be recorded.

4.2 Arrangement of the test object in dry tests

The disruptive-discharge characteristics of a test object with external insulation may be affected by its general arrangement (for example, proximity effects such as distance in air from other live or earthed structures, height above ground level and the arrangement of its high-voltage lead). The general arrangement should be specified by the relevant Technical Committee.

NOTE 1 A clearance to extraneous structures not less than 1,5 times the length of the shortest possible discharge path on the test object usually makes such proximity effects negligible. In wet or pollution tests, or wherever 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 extraneous structures.

NOTE 2 In the case of a.c. or positive switching-impulse voltage tests above 750 kV (peak) the influence of an extraneous structure may be considered as negligible if its distance from the energized electrode is also not less than the height of this electrode above the ground plane. A guide for recommended minimum clearance is given in Figure 1, as a function of the highest test voltage. Significant shorter clearances may be suitable in individual cases. However, an experimental adaptation or a field calculation, taking into account a voltage dependent maximum field strength as described in the literature [1, 2][1], is recommended.

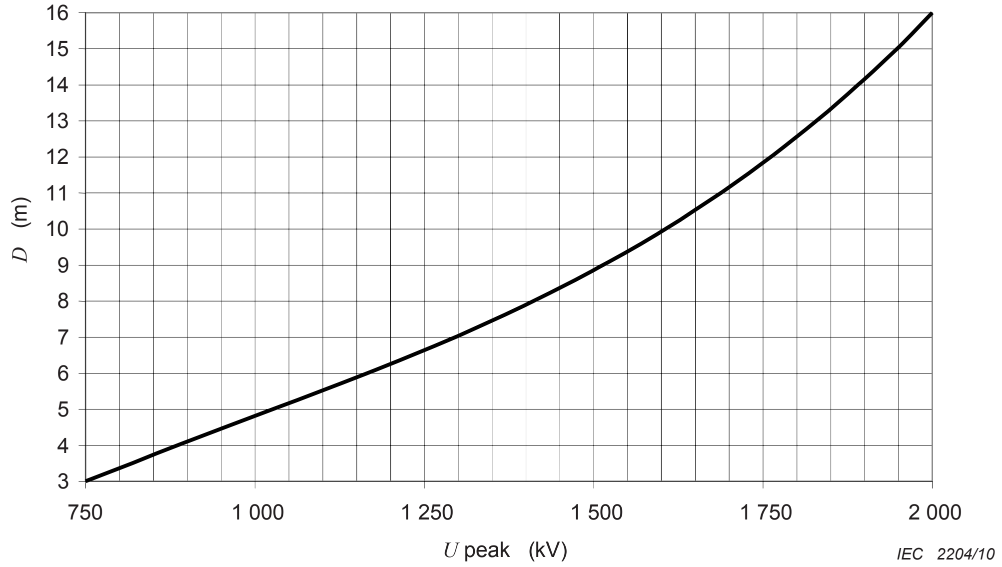


Figure 1 – Recommended minimum clearance *D* of extraneous live or earthed objects to the energized electrode of a test object, during an a.c. or positive switching impulse test at the maximum voltage *U* applied during test

If not otherwise specified by the relevant Technical Committee, the test should be made at ambient atmospheric conditions in the test area without extraneous precipitation or pollution. The procedure for voltage application shall be as specified in the relevant clauses of this standard.

4.3 Atmospheric corrections in dry tests

4.3.1 Standard reference atmosphere

The standard reference atmosphere is:

– temperature t_0 = 20 °C ;

– absolute pressure p_0 = 1 013 hPa (1 013 mbar) ;

– absolute humidity h_0 = 11 g/m^3.

NOTE 1 An absolute pressure of 1 013 hPa corresponds to the height of 760 mm of the mercury column in a mercury barometer at 0 °C. If the barometer height is H mm of mercury, the atmospheric pressure in hectopascal is approximately:

$$p = 1{,}333\ H \text{ hPa}$$

Correction for temperature with respect to the height of the mercury column is considered to be negligible.

NOTE 2 Instruments automatically correcting pressure to sea level are not suitable and should not be used.

4.3.2 Atmospheric correction factors for air gaps

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.

---

[1] Numbers in square brackets refer to the Bibliography.

NOTE Atmospheric corrections do not apply to flashover, only to sparkover.

The disruptive-discharge voltage is proportional to the atmospheric correction factor K_t that results from the product of two correction factors:

- the air density correction factor k_1 (see 4.3.4.1);
- the humidity correction factor k_2 (see 4.3.4.2).

$$K_t = k_1 k_2$$

4.3.3 Application of correction factors

4.3.3.1 Standard procedure

By applying correction factors, a disruptive-discharge voltage measured in given test conditions (temperature t, pressure p, humidity h) may be converted to the value, which would have been obtained under the standard reference atmospheric conditions (t_0, p_0, h_0).

Disruptive-discharge voltages, U, measured at given test conditions are corrected to U_0 corresponding to standard reference atmosphere by dividing by K_t:

$$U_0 = U/K_t$$

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

4.3.3.2 Converse procedure

Conversely, where a test voltage is specified for standard reference conditions, it shall be converted into the equivalent value under the test conditions and this may require an iterative procedure.

If not otherwise specified by the relevant Technical Committee, the voltage U to be applied during a test on external insulation is determined by multiplying the specified test voltage U_0 by K_t;

$$U = U_0 K_t$$

However, as U enters into the calculation of K_t, an iterative procedure might have to be used (see Annex E).

NOTE 1 The test for the correct choice of U for the calculation of K_t is to divide U by K_t. If the result is the specified test voltage, U_0, then a correct choice of U has been made. If U_0 is too high, U has to be reduced but if it is too low, it has to be increased.

NOTE 2 When K_t is close to unity, iterative calculation is not necessary.

NOTE 3 In correcting power-frequency voltage the peak value has to be used, because the discharge behaviour is based on the peak value.

4.3.4 Correction factor components

4.3.4.1 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:

$$k_1 = \delta^m$$

where m is an exponent given in 4.3.4.3.

When the temperatures t and t_0 are expressed in degrees Celsius and the atmospheric pressures p and p_0 are expressed in the same units, the relative air density is:

$$\delta = \frac{p}{p_0} \times \frac{273 + t_0}{273 + t}$$

The correction is considered reliable for 0,8 < k_1 < 1,05.

4.3.4.2 Humidity correction factor, k_2

The humidity correction factor may be expressed as:

$$k_2 = k^w$$

where w is an exponent given in 4.3.4.3 and k is a parameter that depends on the type of test voltage and may be obtained as a function of the ratio of absolute humidity, h, to the relative air density, δ, using the following equations (Figure 2):

DC	$k = 1 + 0{,}014(h/\delta - 11) - 0{,}00022(h/\delta - 11)^2$	for 1 g/m^3 < h/δ < 15 g/m^3
AC	$k = 1 + 0{,}012(h/\delta - 11)$	for 1 g/m^3 < h/δ < 15 g/m^3
Impulse	$k = 1 + 0{,}010(h/\delta - 11)$	for 1 g/m^3 < h/δ < 20 g/m^3

NOTE The impulse equation is based on experimental results for positive lightning-impulse waveforms. This equation also applies to negative lightning-impulse voltages and switching-impulse voltages.

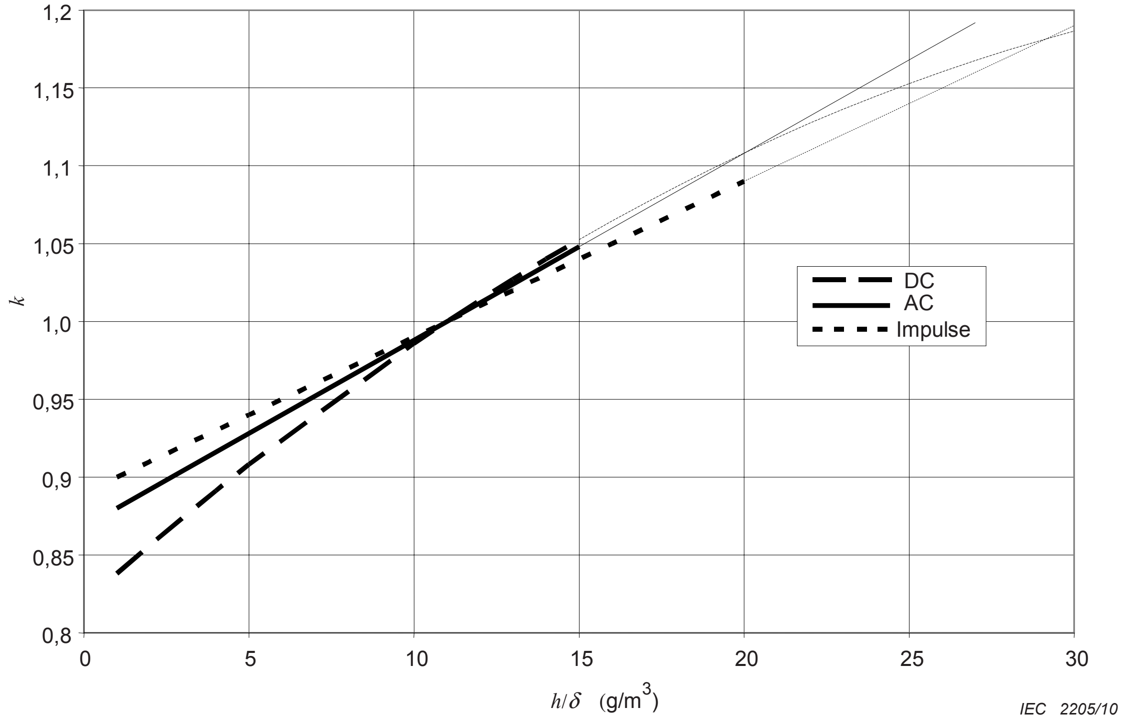


Figure 2 – k as a function of the ratio of the absolute humidity h to the relative air density δ (see 4.3.4.2 for limits of applicability)

For U_m below 72,5 kV (or approximately gap lengths $l < 0{,}5$ m) no humidity correction can at present be specified.

NOTE For specific apparatus, the relevant Technical Committee has specified other procedures (e.g. IEC 62271-1).

4.3.4.3 Exponents *m* and *w*

As the correction factors depend on the type of pre-discharges, this fact can be taken into account by considering the parameter:

$$g = \frac{U_{50}}{500\, L \delta k}$$

where U_{50} is the 50 % disruptive-discharge voltage (measured or estimated) at the actual atmospheric conditions, in kilovolt peak,

L is the minimum discharge path in m,

δ is the relative air density and

k is the dimension less parameter defined in 4.3.4.2.

In the case of a withstand test where an estimate of the 50 % disruptive-discharge voltage is not available, U_{50} can be assumed to be 1,1 times the test voltage, U_0.

The exponents, m and w, are obtained from Table 1 for the specified ranges of g (Figure 3).

Table 1 – Values of exponents, *m* for air density correction and *w* for humidity correction, as a function of the parameter *g*

g	m	w
<0,2	0	0
0,2 to 1,0	$g(g$-0,2)/0,8	$g(g$-0,2)/0,8
1,0 to 1,2	1,0	1,0
1,2 to 2,0	1,0	(2,2-g)(2,0-g)/0,8
>2,0	1,0	0

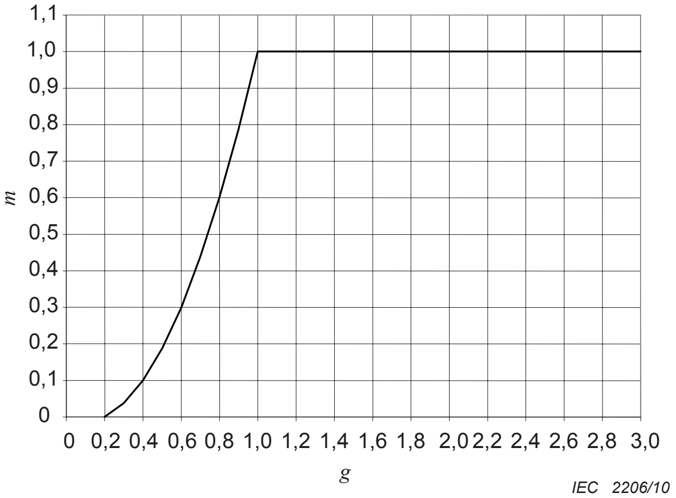


Figure 3a – Values of exponent *m* for air density correction as a function of parameter *g*

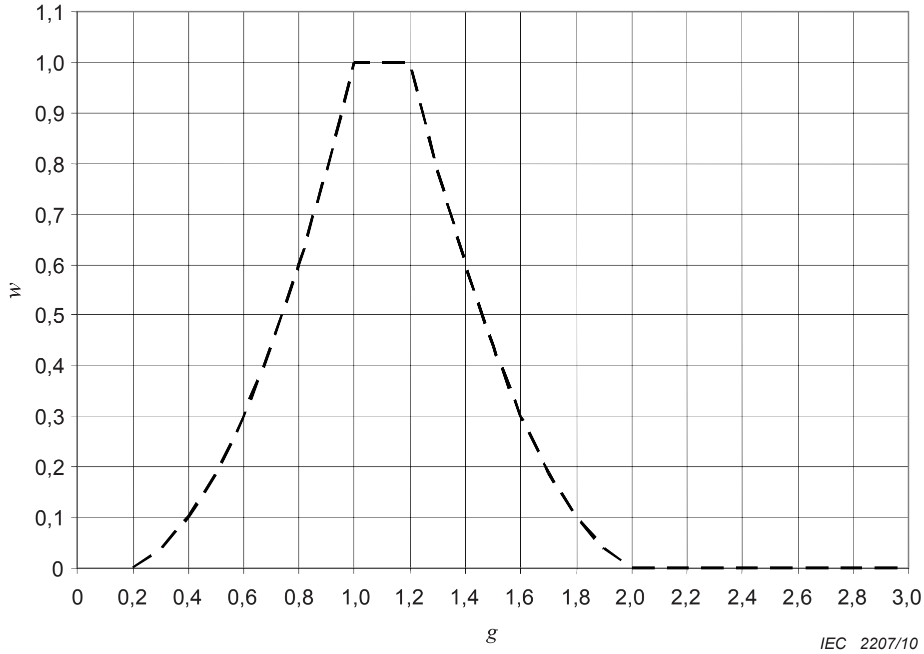


Figure 3b – Values of exponent *w* for humidity correction as a function of parameter *g*

Figure 3 – Values of exponents *m* and *w*

4.3.5 Measurement of atmospheric parameters

4.3.5.1 Humidity

The humidity should preferably be determined with an instrument measuring directly the absolute humidity with an expanded uncertainty not larger than 1 g/m^3.

Measurement of relative humidity and the ambient temperature can also be used for the determination of the absolute humidity, using the formula below, provided that the accuracy of the absolute humidity determination in this case is the same as required above.

$$h = \frac{6{,}11 \times R \times e^{\frac{17{,}6 \times t}{243 + t}}}{0{,}4615 \times (273 + t)}$$

where

h is the absolute humidity in g/m^3,

R is the relative humidity in percent and

t is the ambient temperature in °C.

NOTE This measurement may also be made by means of a ventilated wet and dry bulb hygrometer. The absolute humidity as a function of the thermometer readings is determined from Figure 4, which also permits determination of the relative humidity. It is important to provide adequate airflow so as to reach a steady state and to read the thermometers carefully in order to avoid excessive errors in the determination of the humidity.

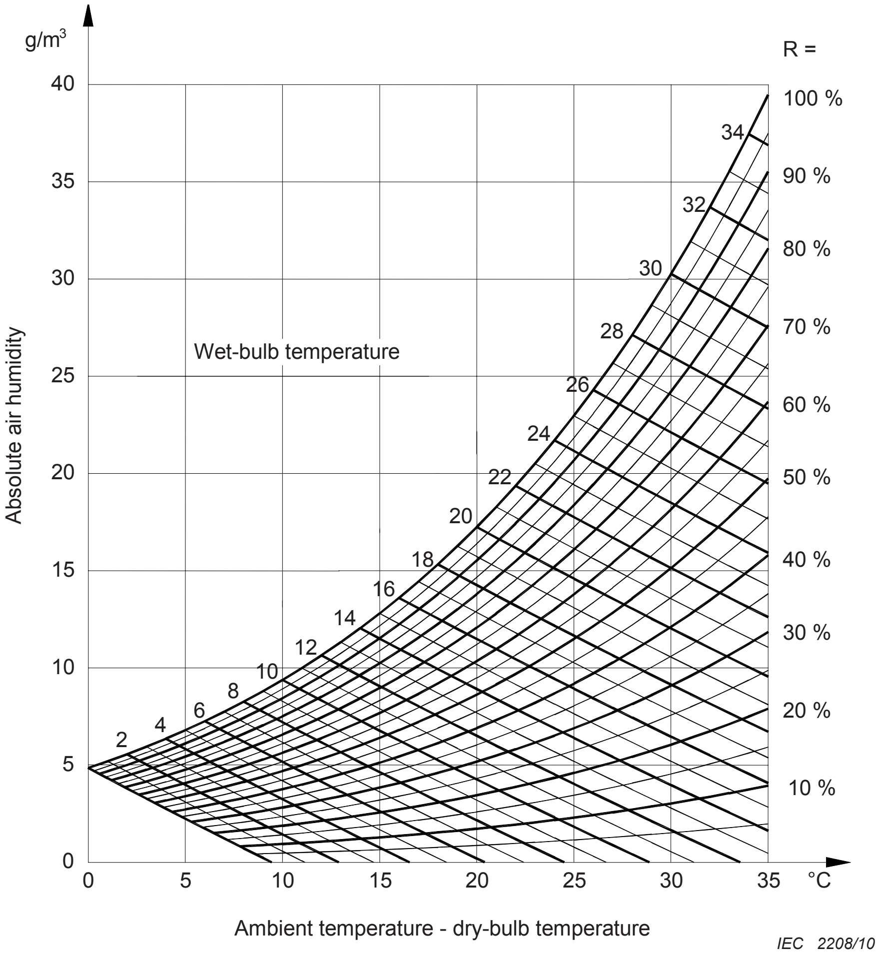


Figure 4 – Absolute humidity of air as a function of dry- and wet-bulb thermometer readings

4.3.5.2 Temperature

The ambient temperature should be measured with an expanded uncertainty of not larger than 1 °C.

4.3.5.3 Absolute pressure

The ambient absolute pressure should be measured with an expanded uncertainty of not larger than 2 hPa.

4.3.6 Conflicting requirements for testing internal and external insulation

While withstand levels are specified under standard reference atmospheric conditions, cases will arise where the application of atmospheric corrections (due to atmospheric conditions differing from the standard reference ones) results in the withstand level for internal insulation appreciably in excess of that for the associated external insulation. In such cases measures to enhance the withstand level of the external insulation shall be adopted to permit application of the correct test voltage to the internal insulation. These measures should be specified by the relevant Technical Committee with reference to the requirements of particular classes of apparatus and could include immersion of the external insulation in liquids or compressed gases.

For 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 especially designed with increased strength. If not, the internal insulation should be tested with the rated value and the external insulation be tested by means of test fixtures unless the relevant Technical Committee states otherwise, in which case it shall specify the test procedure to be used.

4.4 Wet tests

4.4.1 Wet test procedure

This wet test procedure is intended to simulate the effect of natural rain on external insulation. It is recommended for tests with all types of test voltages and on all types of apparatus.

The relevant Technical Committee should specify the arrangement of the test object during the test.

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

The position of the test object relative to the vertical and horizontal rain components shall be specified by the relevant Technical Committee.

In general, the reproducibility of wet test results is less than that for other high-voltage discharge or withstand tests. To minimize the dispersion, the following precautions shall be taken:

- The collecting vessel shall be placed close to the test object, but avoiding the collection of drops or splashes from it. During the measuring period, it should be moved slowly over a sufficient area to average the effect of non-uniformities of the spray from individual nozzles. This measuring zone shall have a width equal to that of the test object and a maximum height of 1 m.
- For test objects between 1 m and 3 m in height, the individual measurements shall be made at the top, centre and bottom of the test object. Each measuring zone shall cover only one third of the height of the test object.
- For test objects exceeding 3 m in height, the number of measuring zones shall be increased to cover the full height of the test object without overlapping.
- The above procedures shall be suitably adapted for test objects having large horizontal dimensions.
- The spread of results may be reduced if the test object is cleaned with a surface-active detergent, which has to be removed before the beginning of wetting.
- The spread of results may also be affected by local anomalous (high or low) precipitation rates. It is recommended to detect these by localized measurements and to improve the uniformity of the spray, if necessary.

The spray apparatus shall be adjusted to produce, within the specified tolerances, precipitation conditions at the test object given in Table 2.

Any type and arrangement of nozzles meeting the requirements given in Table 2 may be used.

Table 2 – Precipitation conditions for standard procedure

Precipitation condition	Unit	Range
Average precipitation rate of all measurements: – vertical component – horizontal component	[mm/min] [mm/min]	1,0 to 2,0 1,0 to 2,0
Limits for any individual measurement and for each component	[mm/min]	±0,5 from average
Temperature of water	[°C]	Ambient temperature ±15
Conductivity of water	[µS/cm]	100 ± 15

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

The test object shall be pre-wetted initially for at least 15 min under the above-specified conditions and these conditions shall remain within the specified tolerances throughout the test, which should be performed without interrupting the wetting. The pre-wetting time shall not include the time needed for adjusting the spray. It is also possible to perform an initial pre-wetting by unconditioned mains water for 15 min, followed without interruption of the spray by a second pre-wetting for at least 2 min before the test begins, using water with all the correct precipitation conditions, which should be measured immediately before starting the test.

Unless otherwise specified by the relevant Technical Committee, the test procedure for wet tests shall be the same as that specified for the corresponding dry tests. The test duration for an a.c. test shall be 60 s, if not otherwise specified. In general, for 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 For a.c. apparatus of large dimensions, such as those having a maximum rated voltage, U_m, higher than 800 kV, no appropriate wet test procedure is available at present.

4.4.2 Atmospheric corrections for wet tests

A density correction factor shall be applied as specified in 4.3, but no humidity correction factor shall be applied for wet tests.

4.5 Artificial pollution tests

Artificial pollution tests are intended to provide information on the behaviour of external insulation under conditions representative of pollution in service, although they do not necessarily simulate any particular service conditions. They are described in IEC 60507.

5 Tests with direct voltage

5.1 Definitions for direct voltage tests

5.1.1
value of the test voltage
arithmetic mean value

5.1.2
ripple
periodic deviation from the arithmetic mean value of the test voltage

5.1.3
ripple amplitude

half the difference between the maximum and minimum values

NOTE In cases where the ripple shape is nearly sinusoidal, true r.m.s. values multiplied by √2 are acceptable for determination of the ripple amplitude.

5.1.4
ripple factor

ratio of the ripple amplitude to the value of test voltage

5.1.5
voltage drop

instantaneous reduction of the test voltage for a short duration of up to a few seconds

NOTE Voltage drop may be caused by non-disruptive discharges.

5.2 Test voltage

5.2.1 Requirements for the test voltage

5.2.1.1 Voltage shape

The test voltage, as applied to the test object, should be a direct voltage with not more than 3 % ripple factor, unless otherwise specified by the relevant Technical Committee.

NOTE Increasing ripple amplitude is directly related to increasing resistive load currents. Dielectric testing where heavy streamers are present may cause excessive ripple and/or voltage drop. Wet testing and pollution testing by their very nature require sources suitable for high resistive currents, see IEC 60507.

5.2.1.2 Tolerances

For test durations not exceeding 60 s, the measured values of the test voltage shall be maintained within ±1 % of the specified level throughout the test. For test durations exceeding 60 s, the measured value of the test voltage shall be maintained within ±3 % of the specified level throughout the test.

NOTE It is emphasized that the tolerance constitutes the permitted difference between the specified value and that actually measured. This difference should be distinguished from the uncertainty of a measurement (see 3.3.1).

The source characteristics should be sufficient to allow charging of the capacitance of the test object in a reasonably short time. In the case of wet or pollution tests, the source, including its storage capacitance, should also be adequate to supply the transient discharge currents of the test object with a voltage drop of < 10 %.

5.2.2 Generation of the test voltage

The test voltage is generally obtained by means of transformer rectifier circuits. 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 value and nature of the test current to be supplied, the important constituents of which are indicated in 5.2.4.

5.2.3 Measurement of the test voltage

The measurement of the arithmetic mean value, the ripple factor and any transient in the test voltage shall be made with approved measuring systems (see IEC 60060-2).

Attention is drawn to the requirements the on response characteristics of converting devices used for measuring ripple, transients or voltage stability.

5.2.4 Measurement of the test current

When measurements of current are made through the test object, 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 consist of:

- the capacitive current, due to the initial application of the test voltage and to any ripple or other fluctuations imposed on it;
- the dielectric absorption current, due to slow charge displacements within the insulation and persisting for periods of a few seconds up to several hours. This process is partially reversible, currents of the opposite polarity being observed when the test object is discharged and short-circuited;
- the continuous leakage current, which is the final steady direct current attained at constant applied voltage after the above components have decayed to zero;
- partial discharge currents.

Measurement of the first three components necessitates 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 may sometimes be obtained by observing current variations with respect to time, during non-destructive tests.

The relative magnitude and the importance of each component of current depend on the type and the condition of the test object, the purpose for which the test is being made and the duration of the test. Accordingly, the measurement procedures should be specified by the relevant Technical Committee, especially when it is required to distinguish a particular component.

Current measurements shall be made with a calibrated measuring system.

Measurements of partial discharge pulse currents are made with special instruments, which are dealt with in IEC 60270.

NOTE Voltage protective devices should always be used in d.c. current measurement circuits due to the possibility of disruptive-discharge currents occurring that are much larger than the normal currents.

5.3 Test procedures

5.3.1 Withstand voltage tests

The voltage should 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 reading of the measuring instruments, but not so slowly as to cause unnecessary prolongation of stress to the test object near the test voltage U. These requirements are in general met if the rate of rise is about 2 % of U per second when the applied voltage is above 75 % of U. It 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 duration shall be specified by the relevant Technical Committee taking into consideration that the time to reach the steady-state voltage distribution depends on the resistances and capacitances of the test object components. When not otherwise specified by the relevant Technical Committee, the duration of a withstand test shall be 60 s.

The polarity of the voltage or the order in which voltages of each polarity are applied, and any required deviation from the above specifications, shall be specified by the relevant Technical Committee.

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

5.3.2 Disruptive-discharge voltage tests

The voltage shall be applied and raised continuously, as for a withstand voltage test, until a disruptive discharge occurs on the test object. The last value of the test voltage recorded before the instant of the disruptive discharge shall be recorded. This shall be repeated for the number of times n specified in the test procedure to give a set of n measured voltages.

The relevant Technical Committee shall specify the rate of voltage rise, the number of voltage applications and the procedure for evaluating the test results (see Annex A).

5.3.3 Assured disruptive-discharge voltage tests

The voltage shall be applied and raised continuously, as for a withstand voltage test, until a disruptive discharge occurs on the test object. The last value of the test voltage reached just before the instant of the disruptive discharge shall be recorded. This shall be repeated for the number of times n specified in the test procedure to give a set of n measured voltages.

The requirements of the test are satisfied if no voltage in this set exceeds the assured disruptive-discharge voltage.

The relevant Technical Committee shall specify the number of voltage applications and the rate of voltage rise.

6 Tests with alternating voltage

6.1 Definitions for alternating voltage tests

6.1.1

peak value of an alternating voltage
average of the magnitudes of the positive and negative peak values

NOTE In many cases instruments measuring only one polarity peak are used. Measuring only one polarity is acceptable as long as waveform symmetry is within the limits set in 6.2.1.1.

6.1.2

value of the test voltage
its peak value divided by $\sqrt{2}$

NOTE The relevant Technical Committee may require a measurement of the r.m.s. value of the test voltage instead of the peak value for cases where the r.m.s. value may be of importance, for instance, when thermal effects are involved.

6.1.3

r.m.s. value
square root of the mean value of the square of the voltage values during a complete cycle

6.1.4

voltage drop
instantaneous reduction of the test voltage for a short duration of up to a few periods

6.2 Test Voltage

6.2.1 Requirements for the test voltage

6.2.1.1 Voltage waveshape

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

NOTE IEC 60060-3 describes alternating test voltages for frequencies from 10 Hz to 500 Hz.

The voltage waveshape shall approximate to a sinusoid with the difference of the magnitudes of the positive and negative peak values being less than 2 %.

The results of a high-voltage test are thought to be unaffected by small deviations from a sinusoid if the ratio of peak to r.m.s. values equals $\sqrt{2}$ within ±5 %.

For some test circuits in common use greater deviations have to be accepted. Note that the test object, especially if it has non-linear characteristics, may considerably affect the deviation from a sinusoid.

NOTE In addition to the above requirement, the total harmonic distortion (THD) can be used to characterize the wave shape distortion as this might be important for partial discharge pattern recognition measurements. Specifications may be given by the relevant Technical Committee.

6.2.1.2 Tolerances

For test durations not exceeding 60 s, the measured values of the test voltage shall be maintained within ±1 % of the specified level throughout the test. For test durations exceeding 60 s the measured value of the test voltage shall be maintained within ±3 % of the specified level throughout the test.

The test voltage source including the supporting capacitances should be adequate to supply the transient discharge currents also in the case of wet and pollution tests with a voltage drop of </= 20 %.

NOTE It is emphasized that the tolerance constitutes the permitted difference between the specified value and that actually measured. This difference should be distinguished from the uncertainty of a measurement (see 3.1.1).

6.2.2 Generation of the test voltage

6.2.2.1 General requirements

The test voltage is generally supplied from a step-up transformer. Alternatively, it may be generated by means of a series-resonant or parallel-resonant circuit.

The voltage in the test circuit shall be stable enough to be practically unaffected by varying leakage currents. Non-disruptive discharges in the test object shall 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.

NOTE Attention is drawn to the possibility that such non-disruptive discharges may cause large over swings of voltage between the terminals of the test object. This phenomenon may cause failure of the test object or of the testing source. Introduction of a resistance to the high-voltage circuit can dampen such overvoltage transients but the resistance should be of a sufficiently low value so as not to affect the test voltage delivered to the test object.

The total capacitance of the test object and of any additional capacitor should be sufficient to ensure that the measured disruptive-discharge voltage is unaffected by non-disruptive partial discharges or pre-discharges in the test object. A capacitance in the range from 0,5 nF to 1,0 nF is generally sufficient.

6.2.2.2 Requirements for the transformer test circuit

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

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

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

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

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

For tests under artificial pollution, steady state current ratings of 1 A to 5 A may be necessary. See IEC 60507.

6.2.2.3 The series-resonant circuit

The series-resonant circuit consists essentially of an inductor in series with a capacitive test object or load connected to a medium-voltage power source. Alternatively it may consist of a capacitor in series with an inductive test object. By varying the circuit parameters or the supply frequency, the circuit can be tuned to resonance, when a voltage considerably greater than that of the source and of substantially sinusoidal shape is applied to the test object.

The stability of the resonance conditions and of the test voltage depends on the stability of the supply frequency and of the test system characteristic, described by the quality factor, which is the ratio between test reactive power and power loss.

When a discharge occurs, the circuit capacitance discharges instantaneously and then the follow-through current from the source is relatively low. The limited follow-through current generally results in less damage to the test object.

The series-resonant circuit is especially useful when testing capacitive objects in which the leakage currents on the external insulation are small in comparison with the capacitive currents through the test object or the energy to form a disruptive discharge is very small. A series resonant circuit can supply higher leakage currents as additional capacitance is added to the circuit. A series-resonant circuit is also useful for testing reactors with sufficient circuit capacitance.

The series resonant circuit may be unsuitable for testing external insulation under wet or polluted conditions, unless the requirements of 6.2.2.1 are satisfied. In general, wet tests can be performed with adequate preload capacitance added.

6.2.3 Measurement of the test voltage

The measurement of the value of the test voltage, the r.m.s. value, and the transient drops shall be made with an approved measuring system (see IEC 60060-2).

6.2.4 Measurement of the test current

The current is usually measured by a conventional current transformer coupled to the ground lead of the test object. It can also be measured in the high-voltage lead to the test object.

Current measurements shall be made with a calibrated measuring system.

NOTE The current can also be measured in the earthed lead of the step-up transformer or resonance reactor, provided the current of any parallel capacitor can be neglected.

6.3 Test procedures

6.3.1 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 or due to uncontrolled resonance conditions. It should be raised sufficiently slowly to permit reading of the measuring instrument but not so slowly as to cause unnecessary prolongation of the stressing of the test object near to the test voltage U. These requirements are in general met if the rate of rise is about 2 % of U per second, when the applied voltage is above 75 % of U. It shall be maintained for the specified time and then rapidly decreased, but not suddenly interrupted as this may generate switching transients, which could cause damage or erratic test results.

The test duration shall be specified by the relevant Technical Committee and shall be independent of the frequency in the range from 45 Hz to 65 Hz. If not specified by the relevant Technical Committee the duration of a withstand test shall be 60 s.

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

6.3.2 Disruptive-discharge voltage tests

The voltage shall be applied and raised continuously, as for a withstand voltage test, until a disruptive discharge occurs on the test object. The last value of the test voltage recorded before the instant of the disruptive discharge shall be recorded. This shall be repeated for the number of times n specified in the test procedure to give a set of n measured voltages.

The relevant Technical Committee shall specify the rate of rise of the voltage, the number of voltage applications and the procedure for evaluating the test results (see Annex A).

6.3.3 Assured disruptive-discharge voltage tests

The voltage shall be applied and raised continuously, as for a withstand voltage test, until a disruptive discharge occurs on the test object. The last value of the test voltage recorded before the instant of the disruptive discharge shall be recorded. This shall be repeated for the number of times n specified in the test procedure to give a set of n measured voltages.

The requirements of the test are satisfied if no voltage in this set exceeds the assured disruptive-discharge voltage.

The relevant Technical Committee shall specify the number of voltage applications and the rate of rise of the voltage.

7 Tests with lightning-impulse voltage

7.1 Definitions for lightning-impulse voltage tests

7.1.1
impulse voltage
intentionally applied aperiodic transient voltage, which usually rises rapidly to a peak value and then falls more slowly to zero

NOTE For special purposes, impulses having approximately linearly rising fronts or transients of oscillating or approximately rectangular form are used.

7.1.2
lightning-impulse voltage
impulse voltage with a front time less than 20 µs

7.1.3
full lightning-impulse voltage
lightning-impulse voltage, which is not interrupted by a disruptive discharge (see Figure 5)

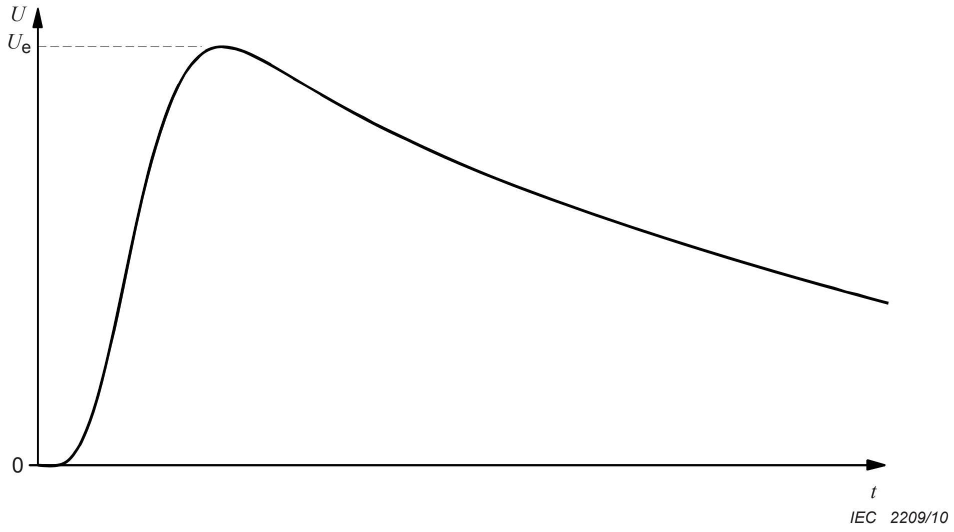


Figure 5 – Full lightning-impulse voltage

7.1.4
overshoot
increase of amplitude of an impulse voltage due to a damped oscillation at the peak caused by the circuit

NOTE Such oscillations (frequency range usually 0,1 MHz to 2 MHz) are caused by circuit inductance and sometimes cannot be avoided in large circuits or for inductive test objects. Methods for evaluation of overshoot are given in Annex B.

7.1.5
recorded curve
graphical or digital representation of the test data of an impulse voltage

7.1.6
base level
level of a record of an impulse measuring system when there is zero input to the recording instrument

7.1.7
base curve

estimate of a full lightning-impulse voltage without a superimposed oscillation (see Annex B)

7.1.8
residual curve

$R(t)$

difference between the recorded curve and the base curve (see Annex B)

7.1.9
extreme value

U_e

maximum value of the recorded curve measured from the base level in the same sense as the applied impulse

7.1.10
base curve maximum

U_b

maximum value of the base curve

7.1.11
test voltage function

amplitude-frequency function which is defined to represent the response of insulation to impulses with overshoot. It is given by:

$$k(f) = \frac{1}{1 + 2{,}2 f^2}$$

where f is the frequency in MHz (see Figure 6).

NOTE 1 Different test voltage curves for different types of insulation may be specified by the relevant Technical Committee when more test data becomes available.

NOTE 2 Applying this function as a filter to the residual voltage curve allows the calculation of the value of the test voltage of the equivalent full lightning-impulse voltage (see Annex B, Annex C and Annex D).

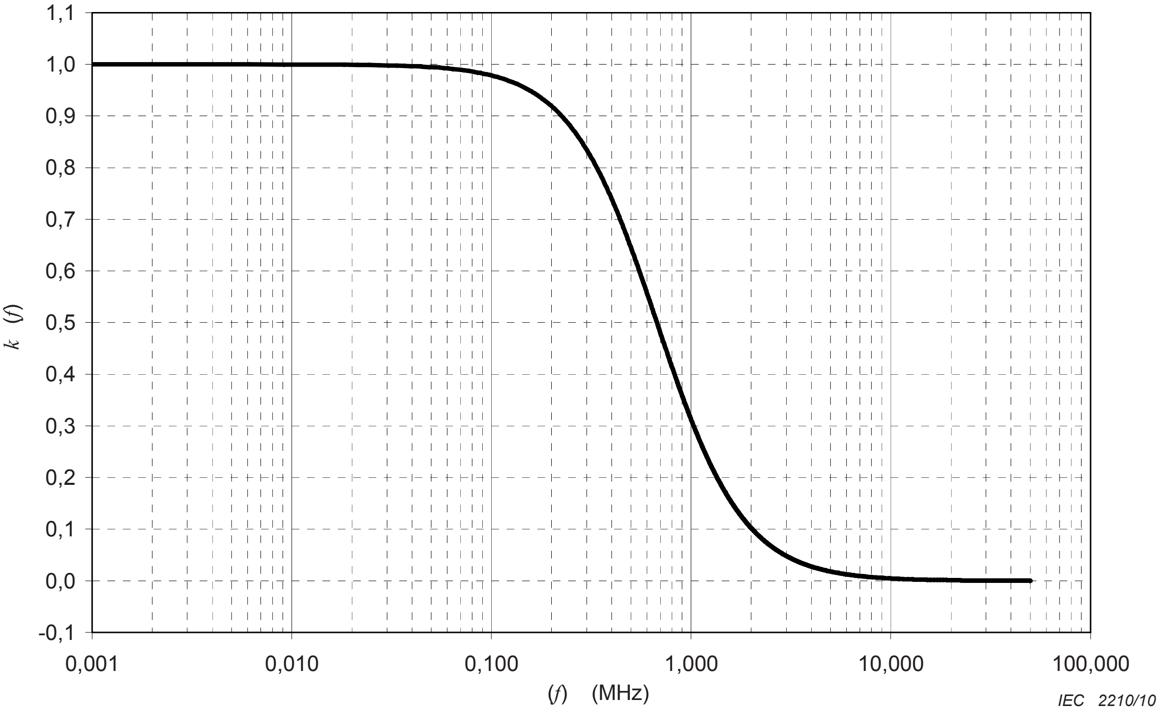


Figure 6 – Test voltage function

7.1.12
filtered residual curve
$R_f(t)$
residual curve filtered by the test voltage function

7.1.13
test voltage curve
summation of the base curve and the filtered residual curve

NOTE This is a mathematical representation of the filtering process and is not a physical entity or an equivalent impulse.

7.1.14
equivalent smooth impulse
estimated lightning-impulse voltage without overshoot having a peak value equal to the maximum value of the test voltage curve and the same front time and time to half-value as the related test voltage curve

NOTE An equivalent smooth impulse has the same dielectric breakdown behaviour as the recorded curve.

7.1.15
value of the test voltage
U_t
maximum value of the test voltage curve measured from the base level in the same sense as the applied impulse

7.1.16
overshoot magnitude
β
difference between the extreme value of the recorded curve and the maximum value of the base curve

7.1.17
relative overshoot magnitude
β'
ratio of the overshoot magnitude to the extreme value, usually expressed as a percentage

7.1.18
front time
T_1
virtual parameter defined as 1/0,6 times the interval T between the instants when the impulse is 30 % and 90 % of the peak value on the test voltage curve (points A and B, Figure 7)

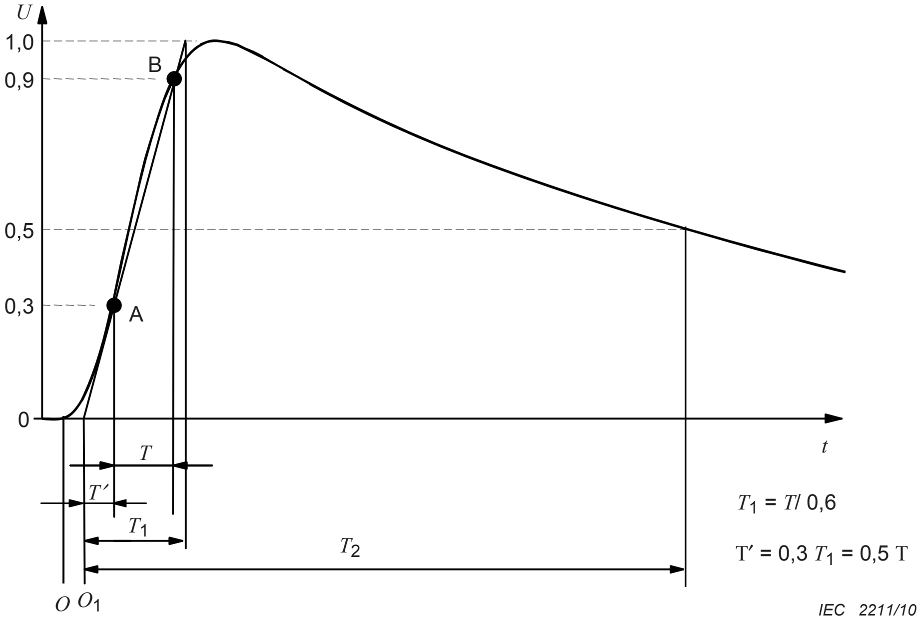


Figure 7 – Full impulse voltage time parameters

7.1.19
virtual origin
O_1
instant preceding that corresponding to point A, of the test voltage curve (see Figure 7) by a time 0,3 T_1

NOTE For records having linear time scales, this is the intersection with the time axis of a straight line drawn through the reference points A and B on the front.

7.1.20
average rate of rise
slope of the best fitting straight line, calculated from the recorded curve, using all the data points between the 30 % and 90 % of the extreme value levels and usually expressed in kilovolts per microsecond

NOTE In the case of noise or oscillations at the 30 % and 90 % levels, the data set is bounded by the first point after the last crossing of the 30 % level and by the last point before the first crossing of the 90 % level.

7.1.21
peak time
T_e
extreme value, U_e, divided by the average rate of rise

7.1.22
time to half-value

T_2

virtual parameter defined as the time interval between the virtual origin, O_1, and the instant when the test voltage curve has decreased to half the test voltage value (see Figure 7)

7.1.23
voltage time interval

T_λ

time interval for which the recorded curve exceeds λU_e where $0 < \lambda < 1$ (see Figure 8)

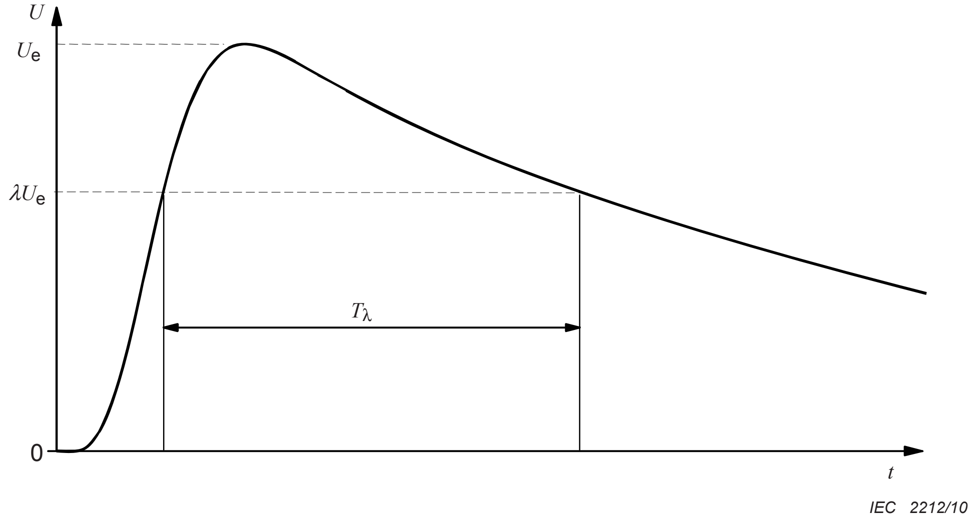


Figure 8 – Voltage time interval

7.1.24
voltage integral

integral of the recorded curve with respect to time over a specified time interval (see Figure 9).

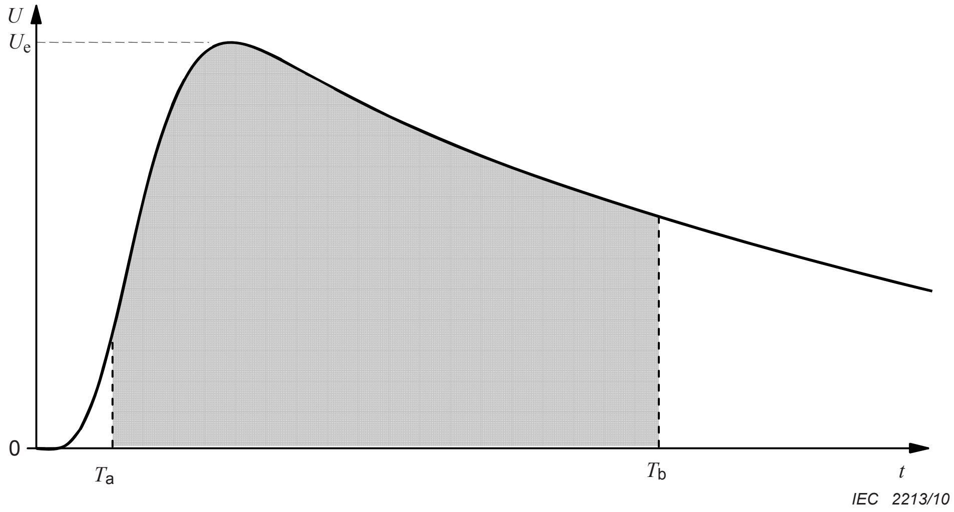


Figure 9 – Voltage integral

7.1.25
chopped lightning-impulse voltage

lightning-impulse voltage during which a disruptive discharge causes a rapid collapse of the voltage, practically to zero value (see Figure 10 to Figure 12).

7.1.26
instant of chopping

instant at which the extrapolation of the line between the 70 % and 10 % points (C and D) on the voltage collapse crosses the level immediately before the collapse (see Figure 10 and Figure 11).

7.1.27
time to chopping

T_C

virtual parameter defined as the time interval between the virtual origin O_1 and the instant of chopping (see Figure 10 and Figure 11).

7.1.28
characteristics related to the voltage collapse during chopping

two points C and D at 70 % and 10 % of the voltage immediately before the voltage collapse (see Figure 11)

NOTE 1 The duration of the voltage collapse is defined as 1/0,6 times the time interval between points C and D. The steepness of the voltage collapse is the ratio of the voltage at the instant of chopping to the duration of voltage collapse.

NOTE 2 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 systems.

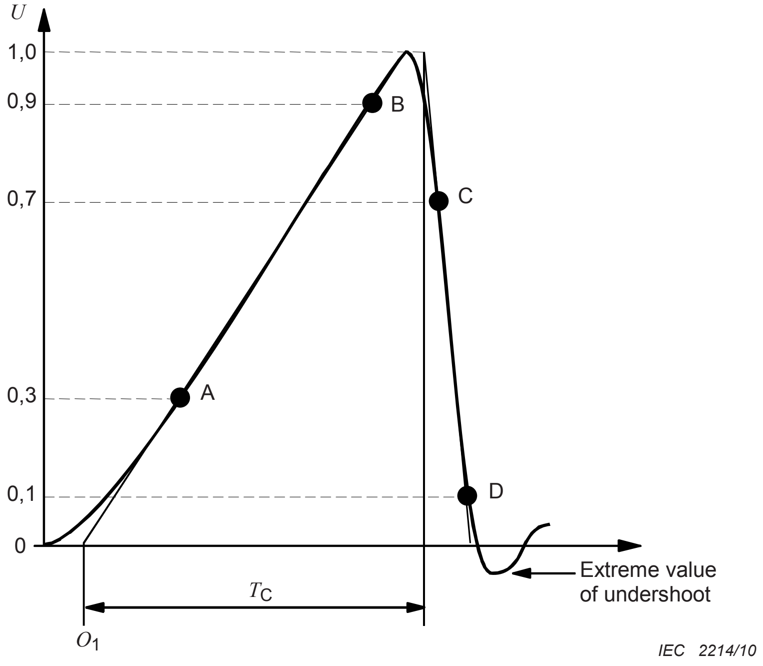


Figure 10 – Lightning-impulse voltage chopped on the front

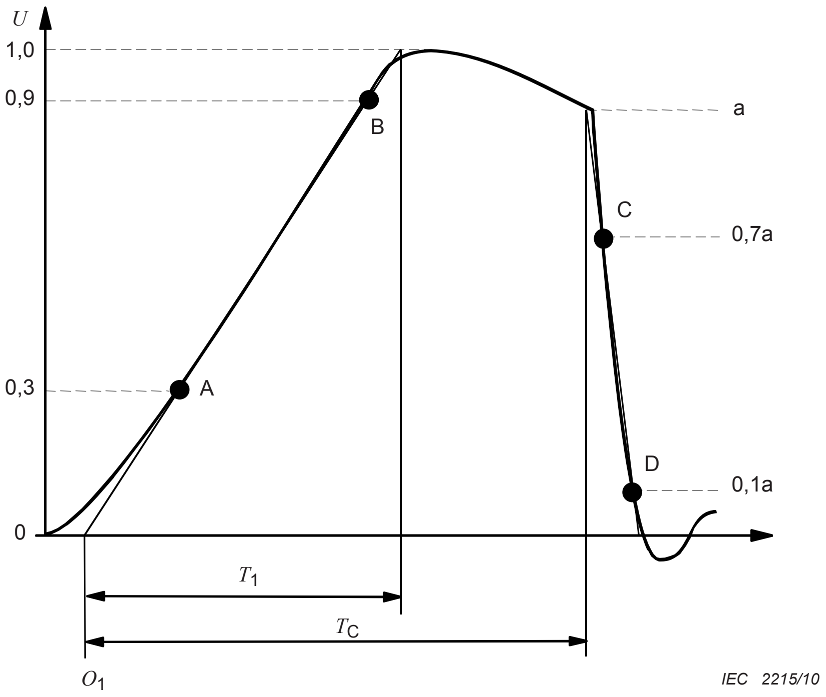


Figure 11 – Lightning-impulse voltage chopped on the tail

7.1.29
extreme value of the undershoot of an impulse
maximum amplitude measured from the base level in the opposite sense to the applied impulse (see Figure 10).

7.1.30
linearly rising front-chopped impulse
voltage rising with approximately constant steepness, until it is chopped by a disruptive discharge

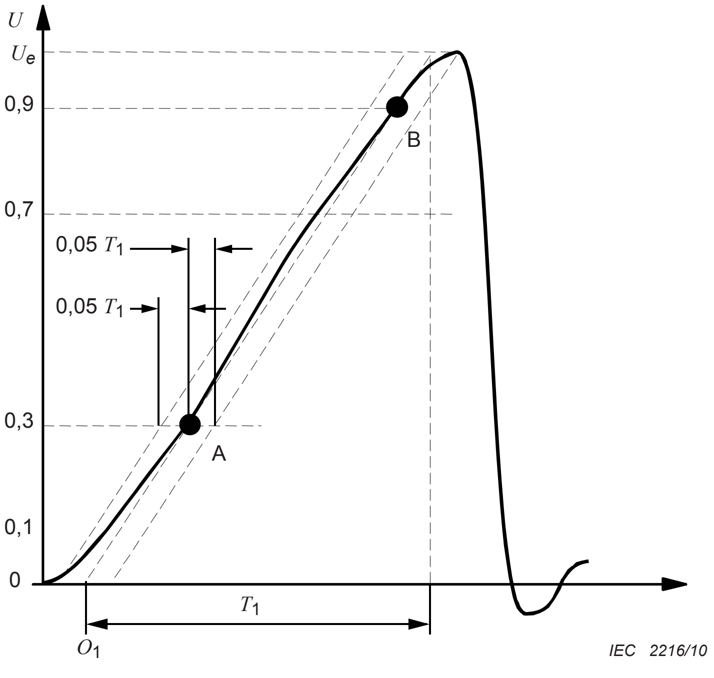


Figure 12 – Linearly rising front chopped impulse

NOTE 1 To define such an impulse, the best fitting straight line is drawn through the part of the front between 30 % and 90 % of the peak magnitude; the intersections of this with the 30 % and 90 % voltage values then being designated A and B, respectively (see Figure 12).

The impulse is defined by:

- the maximum voltage U_e;
- the front time T_1 and
- the virtual steepness *S*: $S = U_e / T_1$.

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

This chopped impulse is considered to be approximately linearly rising if the front, from 30 % amplitude up to the instant of chopping, is entirely enclosed between two lines parallel to the line AB, but displaced from it in time by ±0,05 T_1 (see Figure 12).

NOTE 2 The value and the tolerance on the virtual steepness S should be specified by the relevant Technical Committee.

7.1.31
Definitions for voltage/time curves

7.1.31.1
voltage/time curve for linearly rising impulse voltage

curve relating the discharge voltage to the front time T_1

NOTE The curve is obtained by applying impulse voltages of different steepness (see Figure 13).

7.1.31.2
voltage/time curve for impulse voltage of constant prospective shape

curve relating the disruptive-discharge voltage of the test object to the time to chopping, which may occur on the front, at the peak or on the tail

NOTE The curve is obtained by applying impulse voltages with different prospective peak values (see Figure 13).

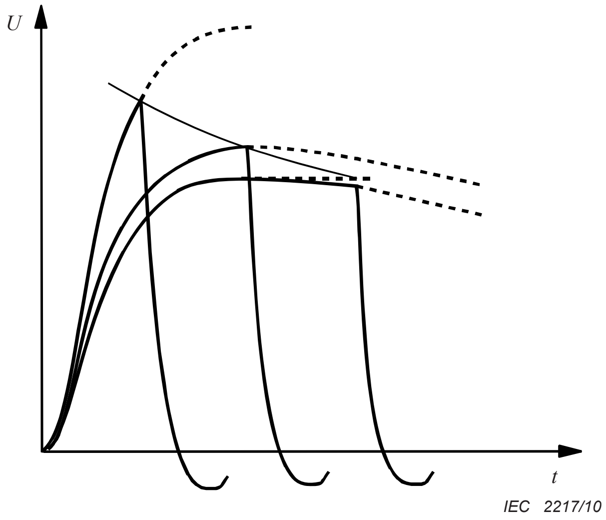


Figure 13 – Voltage/time curve for impulses of constant prospective shape

7.2 Test voltage

7.2.1 Standard lightning-impulse voltage

The standard lightning-impulse voltage is a smooth full lightning-impulse voltage having a front time of 1,2 µs and a time to half-value of 50 µs and described as a 1,2/50 impulse.

7.2.2 Tolerances

If not otherwise specified by the relevant Technical Committee, the following differences are accepted between specified values for the standard impulse and those calculated from the test voltage curve:

- Test voltage value: ±3 %.
- Front time: ±30 %.
- Time to half-value: ±20 %.

If not otherwise specified by the relevant Technical Committee, the relative overshoot magnitude shall not exceed 10 %.

For certain test circuits and test objects, standard waveshapes within the stated tolerances may be impossible to realise. In such cases extension of front time T_1 or overshoot may be necessary. Guidance for such cases should be given by the relevant Technical Committee.

NOTE The peak time, T_e, the voltage time interval, T_λ and the voltage integral are parameters under consideration for alternate characterization of lightning-impulse voltages. Values may be assigned by the relevant Technical Committee.

7.2.3 Standard chopped lightning-impulse voltage

This is a standard impulse chopped by an external gap with a time-to-chopping value between 2 μs to 5 μs.

Other times to chopping may be specified by the relevant Technical Committee. The duration of voltage collapse should be much faster than the front time of the impulse and limits may be set by the relevant Technical Committee. The requirements for measurement and the associated uncertainties are given in IEC 60060-2.

7.2.4 Special lightning-impulse voltages

In some cases oscillating lightning-impulse voltages may be applied. This offers the possibility of producing impulses with shorter front times or with extreme values corresponding to a generator efficiency greater than 1.

NOTE For details see IEC 60060-3.

7.2.5 Generation of the test voltage

The impulse is usually produced by an impulse generator consisting essentially of a number of capacitors that are charged in parallel from a direct voltage source, then switched into series and discharged into an impulse-forming circuit that includes the test object.

7.2.6 Measurement of the test voltage and determination of impulse shape

The measurement of the test voltage value, the time parameters and the overshoot or oscillations on the test voltage shall be made with approved measuring systems (see IEC 60060-2). The measurement shall be made with the test object in the circuit and, in general, the impulse shape shall be checked for each test object. Where a number of test objects of the same design and size are tested under identical conditions, the shape needs only to be verified once.

For a chopped lightning impulse the collapse can occur on the front, at the peak or on the tail. For a front chopped lightning-impulse voltage the test voltage curve is the recorded curve. Impulses chopped on the tail are treated as full waves for the evaluation of test voltage and front time, which can be determined from reduced voltage impulses (e.g. ≤ 50 %) that do not cause chopping. The chopping can be accomplished by an external chopping gap or may occur due to a disruptive-discharge in the internal or external insulation of the test object.

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 the imperfections of the measuring system. Exact determination of the parameters related to chopping requires the presence of both a sharp discontinuity and a fast measuring system. Other cases are left to the relevant Technical Committees for consideration.

Determination of the impulse shape by calculation from the test circuit parameters is not considered to be satisfactory.

7.2.7 Measurement of current during tests with impulse voltages

The relevant Technical Committee shall specify the characteristics of a current flowing in the test object that should be measured during tests with high impulse voltages. When this type of measurement is used for comparative purposes wave shape is of importance and the measurement of the absolute value of this current may be of lesser importance. For guidance see IEC 62475.

7.3 Test procedures

7.3.1 Withstand voltage tests

The recommended test procedure depends on the nature of the test object, as defined in 3.5. The relevant Technical Committee shall specify which procedure shall be applied. In procedures A, B and C the voltage applied to the test object is only the specified withstand value, while in procedure D several voltage levels have to be applied.

NOTE The statistical precision of the procedures is different, but for insulation coordination (IEC 60071) it is assumed that the outcome of the tests is identical.

7.3.1.1 Withstand voltage test: Procedure A

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

NOTE This procedure is recommended for tests on degradable or non-self-restoring insulation.

7.3.1.2 Withstand voltage test: Procedure B

Fifteen impulses of the specified shape and polarity at the specified withstand voltage level are applied to the test object. The requirements of the test are satisfied if not more than two disruptive discharges occur in the self-restoring part of the insulation and if no indication of failure in the non-self-restoring insulation is obtained by the detection methods specified by the relevant Technical Committee.

NOTE If not otherwise specified by the relevant Technical Committee, it could be taken as an indication that no failure has happened in the non-self-restoring insulation, when the last three impulses have not led to a disruptive discharge. In case of a disruptive discharge at one of the impulse numbers 13 to 15, up to three additional pulses can be applied (maximum 18). When no further disruptive discharge occurs, the test object has passed the test.

7.3.1.3 Withstand voltage test: Procedure C

Three impulses of the specified shape and polarity at the specified 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 detection of failure in a non-self-restoring part of insulation is observed with the detection methods specified by the relevant Technical Committee during any part of the test, the test object has failed to pass the test.

7.3.1.4 Withstand voltage test: Procedure D

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

These test methods permit either direct evaluation of U_{10}, and U_{50} or indirect evaluation of U_{10}.

In the latter case U_{10} is derived from the U_{50} value using the relationship:

$$U_{10} = U_{50}(1 - 1{,}3s)$$

The relevant Technical Committee shall specify the value to be assumed for the standard deviation s of the disruptive-discharge voltage. For dry tests on air insulation, without any other insulation involved, the per-unit value s = 0,03 can be used.

The test object is deemed to be satisfactory if U_{10} is not less than the specified impulse withstand voltage.

The following test methods can be used to evaluate U_{50}:

a) the multiple-level method (see Clause A.1.1) with $m \geq 4$ voltage levels, and $n_i \geq 10$ impulses per level;

b) the up-and-down method (see Clause A.1.2) with $n = 1$ impulse per group and $m \geq 20$ useful applications.

To evaluate U_{10} the up-and-down withstand method, with $n = 7$ impulses per group and at least eight useful groups, can be used.

In all cases the voltage interval between levels ΔU should be approximately from 1,5 % to 3 % of the estimated value of U_{50}.

7.3.2 Procedures for assured disruptive-discharge voltage tests

The procedures for an assured disruptive-discharge voltage test are similar to those described in 7.3.1 with the appropriate changes between discharge and withstand conditions.

The relevant Technical Committee may also specify other procedures for specific test objects.

8 Tests with switching-impulse voltage

8.1 Definitions for switching-impulse voltage tests

8.1.1
switching-impulse voltage
impulse voltage with a front time of 20 µs or longer

8.1.2
value of the test voltage
maximum value, if not otherwise specified by the relevant Technical Committee

8.1.3
time to peak
T_p
time interval from the true origin to the time of maximum value of a switching-impulse voltage

NOTE Because of the long duration of the maximum voltage, there can be practical problems in determining this time and methods are given in 8.2.3.

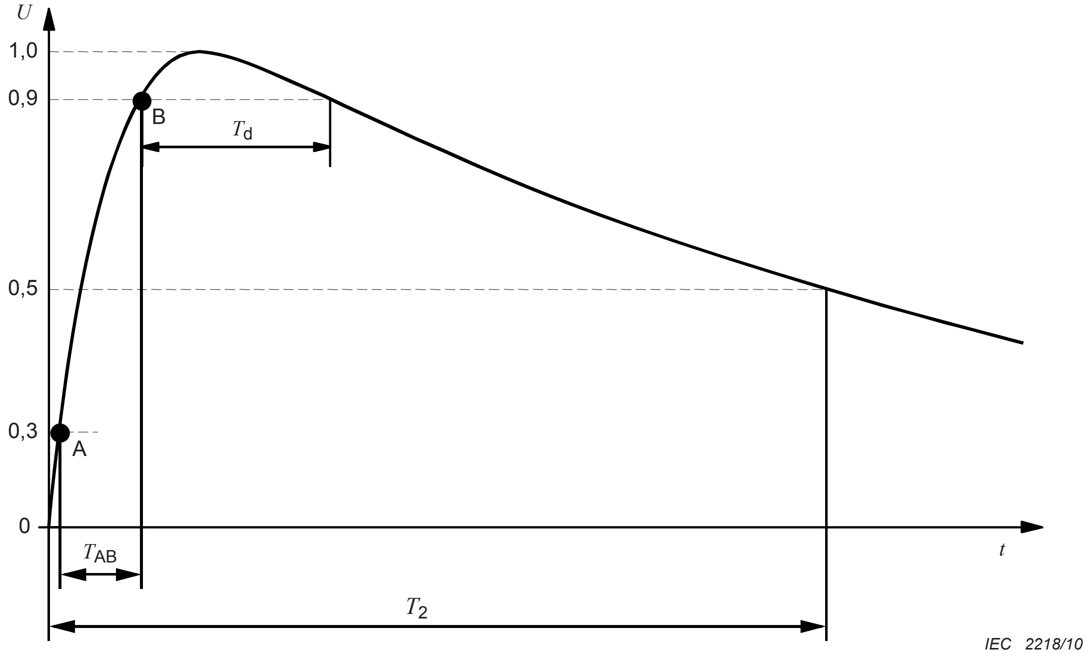


Figure 14 – Switching-impulse voltage

8.1.4
true origin
O
instant where the recorded curve begins a monotonic increase (or decrease)

8.1.5
time to half-value
T_2
time interval between the true origin and the instant when the voltage has first decreased to half the maximum value (see Figure 14)

8.1.6
time above 90 %
T_d
time interval during which the switching-impulse voltage exceeds 90 % of its maximum value (see Figure 14)

8.1.7
time to zero
T_z
time interval between the true origin and the instant when the voltage has its first passage through zero

NOTE Specification of the time above 90 % and time to zero instead of the time to half-value is found useful, for instance, when the form of the impulse is dictated by saturation phenomena in the test object or the test circuit, or where the severity of the test on important parts of internal insulation of the test object is considered to be highly dependent on these parameters. When specifying a switching-impulse voltage, 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 $T_p/T_d/T_z$, impulse.

Additional parameters may be specified by the relevant Technical Committee when considering specific tests.

8.2 Test voltage

8.2.1 Standard switching-impulse voltage

The standard switching-impulse voltage is an impulse having a time to peak T_p of 250 µs and a time to half-value T_2 of 2 500 µs. It is described as a 250/2 500 impulse.

8.2.2 Tolerances

If not otherwise specified by the relevant Technical Committee, the following differences are accepted between specified values and those actually recorded, both for standard and special impulses:

Value of the test voltage	±3 %
Time to peak	±20 %
Time to half-value	±60 %

In certain cases, for instance with low impedance 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 relevant Technical Committee.

8.2.3 Time-to-peak evaluation

8.2.3.1 Standard switching-impulse voltages

For standard switching-impulse voltages:

$$T_p = K\,T_{AB},$$

where K is a dimensionless constant given by

$$K = 2{,}42\text{-}3{,}08\text{x}10^{-3}\,T_{AB} + 1{,}51\text{x}10^{-4}\,T_2$$

and where T_{AB} and T_2 are in microseconds and $T_{AB} = t_{90} - t_{30}$.

NOTE In IEC 60060-3 $T_p = 2{,}4\ T_{AB}$, is used for standard switching-impulse voltages.

8.2.3.2 Non-standard impulses

For non-standard impulses, the time to peak can be determined by various methods of digital curve fitting dependant on the actual shape.

NOTE If required by uncertainty considerations, the method of time-to-peak evaluation should be stated.

8.2.4 Special switching-impulse voltages

For special purposes, when the use of the standard switching-impulse voltage is not considered sufficient or appropriate, special switching-impulse voltages of either aperiodic or oscillating form may be prescribed by the relevant Technical Committee.

NOTE For details of oscillating switching-impulse voltages see IEC 60060-3.

8.2.5 Generation of the test voltage

Switching-impulse voltages are usually generated by a conventional impulse generator.

NOTE They can also be generated by the application of a voltage impulse to the low-voltage winding of a testing transformer (or of a transformer to be tested) but it is difficult to reach the standard parameters as specified in 8.2.1 and 8.2.2.

The elements of a circuit for generating switching-impulse voltages should be chosen so as to avoid excessive distortion of the impulse shape due to non-disruptive-discharge currents in the test object. Such currents can reach quite large values, especially during pollution tests on external insulation at high voltages. In test circuits having high internal impedance, they may cause severe distortion of the voltage or even prevent a disruptive discharge from occurring.

8.2.6 Measurement of test voltage and determination of impulse shape

The measurement of the maximum voltage value and the time parameters shall be made with approved measuring systems (see IEC 60060-2). The measurement shall be made with the test object in the circuit and, in general, the impulse shape shall be checked for each test object. Where a number of test objects of the same design and size are tested under identical conditions, the shape needs only to be verified once.

8.2.7 Measurement of current during tests with impulse voltages

The relevant Technical Committee shall specify the characteristics of a current flowing in the test object that should be measured during tests with high impulse voltages. When this type of measurement is used for comparative purposes wave shape is of importance and the measurement of the absolute value of this current may be of lesser importance. For guidance see IEC 62475.

8.3 Test procedures

The test procedures are in general the same as for lightning-impulse voltage testing and similar statistical considerations apply (see 7.3 and Annex A). Unless otherwise specified by the relevant Technical Committee, the standard deviation, in per unit value, of the disruptive-discharge voltage for dry and wet tests on air insulation, without any other insulation involved, can be assumed to be:

$$s = 0{,}06$$

Correspondingly larger voltage intervals ΔU may be used when applying the multiple level or the up-and-down procedures.

NOTE With switching-impulse voltages, disruptive discharges frequently occur at random times well before the peak. In presenting the results of discharge tests made in accordance with 7.3.1.4, the relationship between disruptive-discharge probability and voltage is generally expressed in terms of the prospective maximum value. However, another method is also in use in which the actual disruptive-discharge voltage for every impulse is measured; the probability distribution of the measured voltage values is then determined by the method described for Class 3 tests in Annex A.

9 Tests with combined and composite voltages

9.1 Definitions for combined- and composite-voltage tests

9.1.1

combined voltage

test voltage which appears between the two energized terminals of a three-terminal test object with the third terminal earthed, when energizing is provided by two different test voltages (see Clauses 5 to 8) generated by two separate test voltage sources (see Figure 15).

NOTE Combined voltages are applied for testing, for example, the longitudinal insulation of switching equipment and the phase-to-phase insulation of three-phase systems and equipment. The voltages are applied on different terminals of the test object.

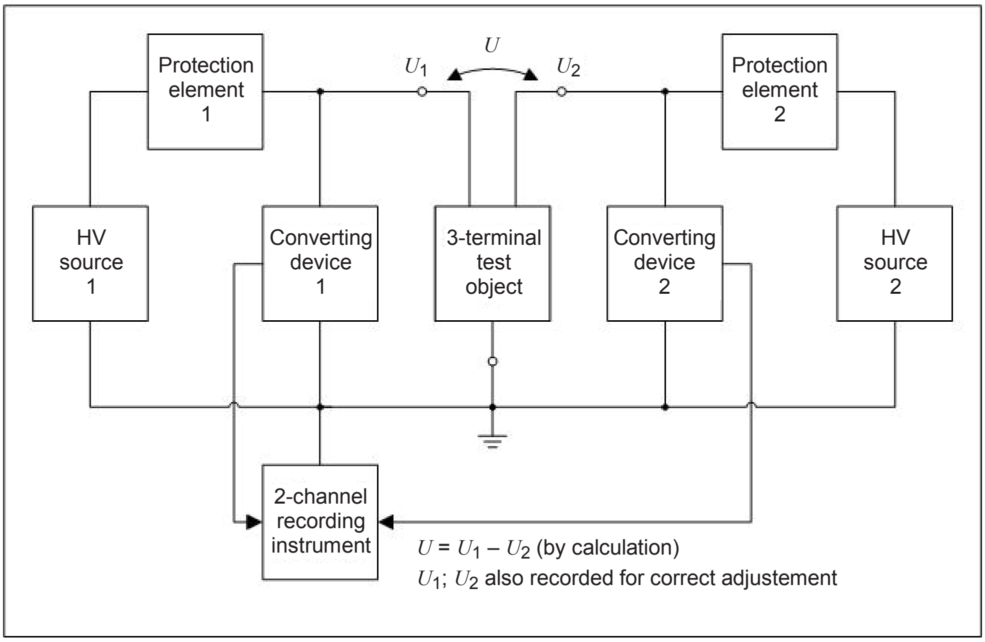


Figure 15 – Circuit for a combined voltage test

9.1.2
value of a combined voltage

maximum potential difference between the two energized terminals of the test object (see Figure 16a)

9.2
composite voltage

superposition of two different test voltages (see Clauses 5 to 8) generated by the suitable connection of two separate test voltages sources (see Figure 16b and Figure 17)

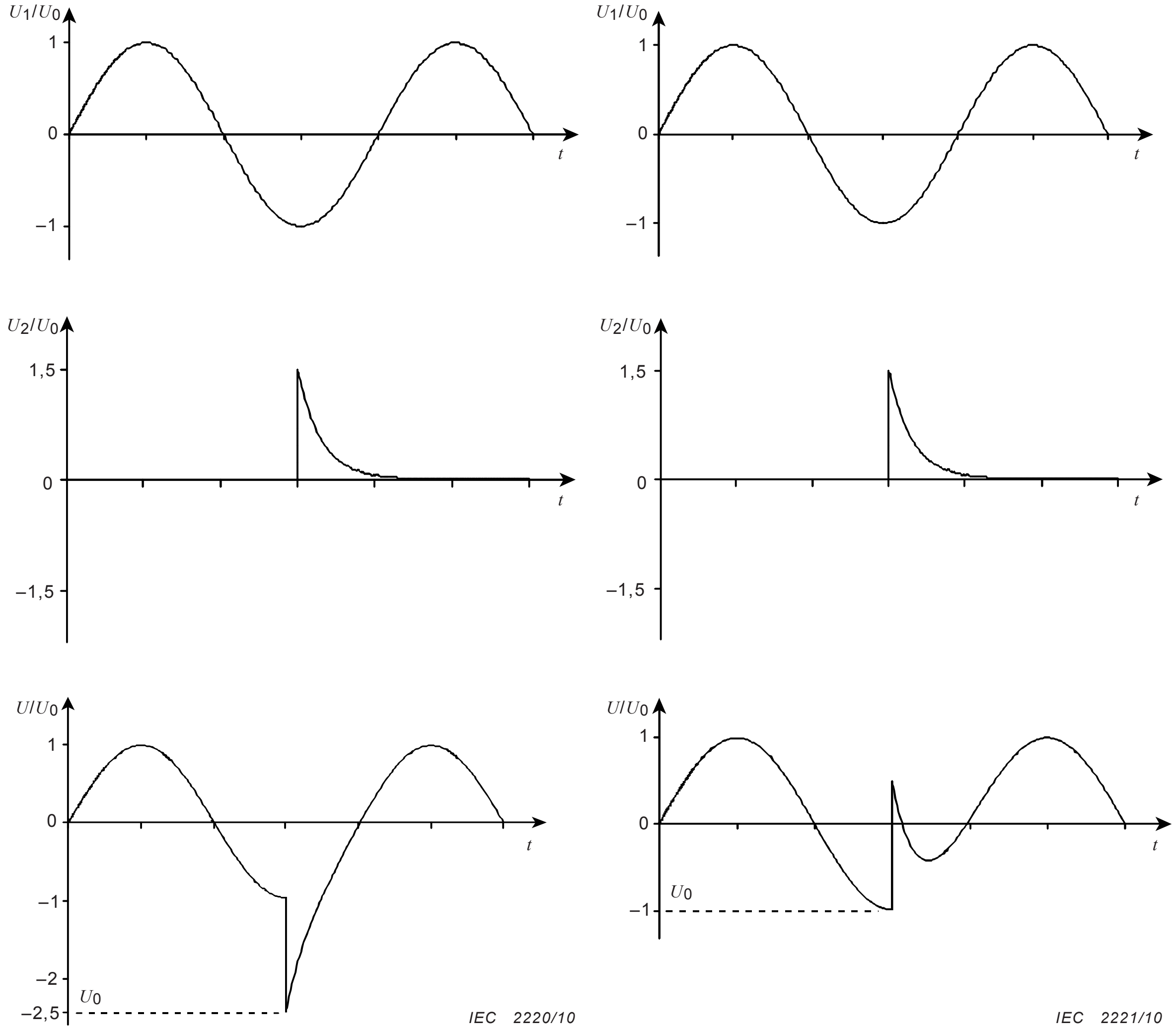
NOTE Both voltages are applied at one terminal of the test object.

9.2.1
value of a composite voltage

maximum absolute value measured at the test object (see Figure 16b)

9.2.2
voltage components

two test voltages, characterized according to the relevant clauses of this standard and causing the combined or composite test voltage stress at the test object



NOTE 1 In Figure 16a, the combined voltage is $U = U_1 - U_2$.

NOTE 2 In Figure 16b, the combined voltage is $U = U_1 + U_2$.

Figure 16a – Combined voltage between two HV terminals

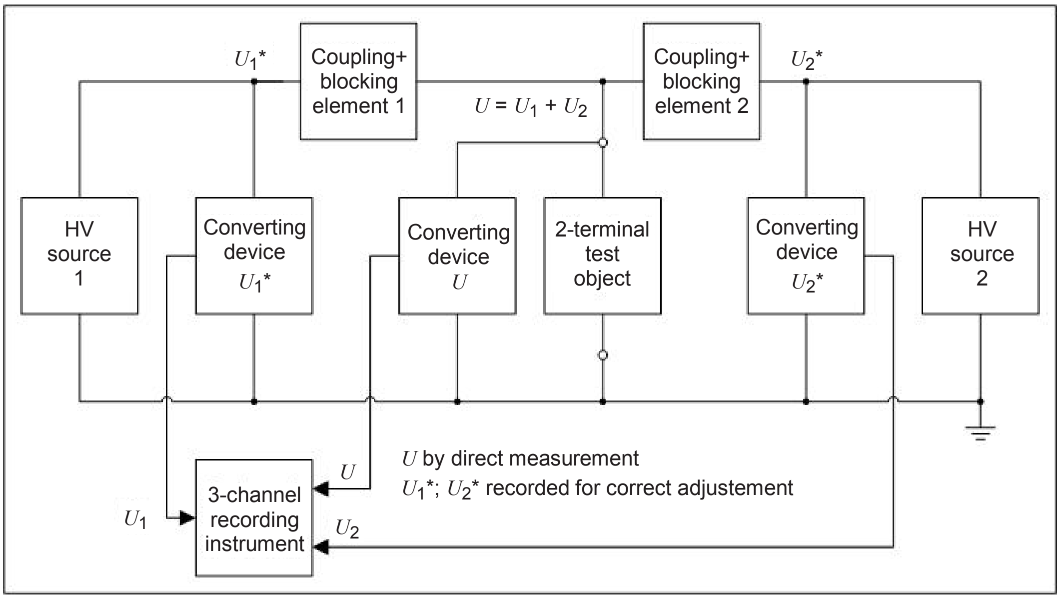
Figure 16b – Combined voltage between one HV terminal and earth

Figure 16 – Schematic example for combined and composite voltage

9.2.3
time delay

Δt

time interval between the instants when the two voltage components reach their maximum values (see Figure 18)



IEC 2222/10

Figure 17 – Circuit for a composite voltage test

9.2.4 Tolerances

If not otherwise specified by the relevant Technical Committee a difference of ± 5 % between a specified and the actually recorded voltage value is acceptable.

The tolerance of the time delay is ± 0,05 T_p, where T_p is the front time or the time to peak of an impulse or a quarter of a cycle of an alternating voltage. T_p is the longer time of the two voltages involved.

9.2.5 Generation

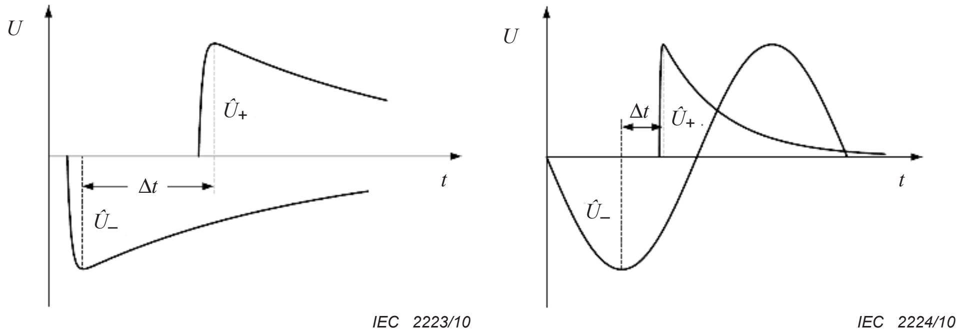
For generation two single voltage sources are connected, each via a protecting element to one of the HV terminals of the test object (Figure 15). The protecting element shall be selected so that the related source in case of a disruptive discharge of the test object is protected against the voltage stress of the other source.

Due to the coupling of the two sources the shapes and amplitudes of the two voltage components will differ from those generated by the same sources used separately. The permitted limits for voltage drop on the a.c. component shall be specified by the relevant Technical Committee.

NOTE See, for example, IEC 62271-1[E5].

9.2.6 Measurement

Both voltage measurement systems arranged between each of the HV terminals of the test object and earth shall fulfil the requirements of IEC 60060-2 for the measurement of both voltage components, because the systems are coupled. See Figure 15. It is recommended to record them by a dual-channel recording instrument according to IEC 61083-1 that enables the direct evaluation of the combined voltage from its two voltage components. The result can be displayed as shown in Figure 16a.



IEC 2223/10

IEC 2224/10

Figure 18a – Combination of two impulse voltages

Figure 18b – Combination of an impulse voltage and a power-frequency alternating voltage

Figure 18 – Definition of time delay Δt

9.3 Composite test voltages

9.3.1 Parameters

A composite test voltage, generated by two voltage components both according to this standard, shall be characterized by the following parameters:

- by its voltage value;
- by the time delay;
- by the parameters of its two components according to the relevant clauses of this standard.

9.3.2 Tolerances

If not otherwise specified by the relevant Technical Committee a difference of ± 5 % between a specified and the actually recorded voltage value is accepted.

The tolerance of the time delay is ± 0,05 T_p, where T_p is the front time or the time to peak of an impulse or a quarter of a cycle of an alternative voltage. T_p is the longer time of the two voltages involved.

9.3.3 Generation

For generation two single voltage sources are connected together and the HV terminal of the test object is at the connection point. See Figure 17. Each connection is realised by an element, which couples one voltage and blocks the other. The interaction of the two sources shall be considered. For the sources itself, see the relevant clauses of this standard.

9.3.4 Measurement

The voltage and time characteristic of the composite voltage shall be measured against earth with a measuring system arranged at the connection point of the test object. See Figure 17. The measuring system shall fulfil the requirements of IEC 60060-2 for both voltage components. It is recommended to also measure the output voltage of each voltage source directly (see Figure 17) and to record the three voltages synchronously.

9.4 Test procedures

Test procedures and arrangement of test objects with combined and composite voltages are left to the relevant Technical Committee.

For atmospheric corrections the parameter g (4.3.4.3) shall be calculated considering the combined or composite test voltage value. The parameter k_1 and k_2 (4.3.4.1 and 4.3.4.2) shall be calculated for the higher of the two test voltages and be applied to both.

Annex A
(informative)

Statistical treatment of test results

A.1 Classification of tests

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

A.1.1 Class 1: Multiple-level tests (Figure A.1)

In a Class 1 test, n_i voltage applications (e.g. lightning-impulse voltages), causing $k_i \leq n_i$ disruptive discharges, are applied at each of m voltage levels, U_i (i = 1, 2, ..., m), with the difference between adjacent voltage levels being $\Delta U = U_{i+1} - U_i$ (i=1,2,...m-1). While this procedure is usually employed with impulse voltages, tests with alternating and direct voltages of specified stressing time also fall into this class.

NOTE The parameters should be selected as follows: $m \geq 5$, $n_i \geq 10$ for all i=1,2,...m; ΔU = (0,01 to 0,06) U_{50}.

The test results are the n_i voltage applications and the corresponding number, k_i, of disruptive discharges at each voltage level U_i (i=1,2,..., m).

A.1.2 Class 2: Up-and-down tests (Figure A.2)

In a Class 2 test, m accepted groups of n essentially equal voltage stresses are applied at voltage levels U_i (i=1,2,..., l). The voltage level for each succeeding group of stresses is increased or decreased by a small amount ΔU according to the result of the previous group of stresses.

Two testing procedures are commonly used: 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 an amount ΔU if no disruptive discharge occurs in a group of n voltage applications, otherwise the voltage level is decreased by the same amount. In the discharge procedure, the voltage level is increased by ΔU if one or more withstands occur; otherwise it is decreased by the same amount.

When n = 1, the two procedures converge to the procedure of the up-and-down 50 % disruptive-discharge voltage test.

Tests with other values of n are also used to determine voltages corresponding to other disruptive-discharge probabilities. The results are the k_i number of stress groups applied at the voltage levels U_i. The first U_i level to be taken into account is that at which at least two preceding groups of stresses have been applied. The total number of useful groups is

$m = \sum_{i=1}^{l} k_i$ at the voltage levels i=1...l.

NOTE Tests with n = 7 give the 10 % and the 90 % disruptive-discharge voltages which are defined as withstand and disruptive voltages respectively (see clause 7.3.1.4). The other parameters should be selected as follows ΔU = (0,01 to 0,03) U_{50} and $m > 15$.

A.1.3 Class 3: Progressive stress tests (Figure A.3)

In a Class 3 test, a procedure always leading to a disruptive discharge on the test object is applied n times. The test voltage may be increased continuously or in steps until a disruptive discharge occurs at a voltage U_i or held constant at a level until a disruptive discharge at time t_i is observed. The results are the n values of voltage U_i or time t_i at which the disruptive discharge has occurred ($n \geq 10$).

Such tests are made with continuously or stepwise increased direct and alternating or stepwise increased impulse voltages. Tests with disruptive discharges occurring on the front of an impulse fall into this class.

A.2 Statistical behaviour of disruptive discharge

When p, the probability of a disruptive discharge during a given test procedure, depends only on the test voltage, U, the behaviour of the test object can be characterized by a function $p(U)$ determined by the processes of discharge development. In practice, this function, the disruptive-discharge probability function, can be represented mathematically by a theoretical probability distribution function characterised by at least two parameters, e. g. U_{50} and s. U_{50} is the estimate of the 50 % discharge voltage for which $p(U)$ = 0,5 and s is the estimate of the standard deviation (see 3.4.4 and 3.4.6).

NOTE 1 Examples of $p(U)$ can be derived from the Gaussian (or Normal), the Weibull or the Gumbel probability distribution functions. Experience shows that for $0{,}16 < p < 0{,}84$, most theoretical distributions can be considered equivalent. For details see the relevant literature [A1-A4].

NOTE 2 Sometimes p is a function of two or more parameters, e.g., U and dU/dt. In such cases, no simple function can be used to describe p. Details of such cases may be found in the technical literature [A1-A4].

The function $p(U)$ and the parameters U_{50} and s can be estimated from tests with sufficient numbers of voltage applications, provided that the characteristics of the test object remain constant throughout the tests. In practice, the number of voltage applications is usually limited and the estimates of U_{50} and s based on an assumed form of $p(U)$ will be subject to statistical uncertainties.

A.2.1 Confidence limits

If a parameter y is estimated from n test results, upper and lower confidence limits (y_{upper} and y_{lower}) can be defined, with the probability C that the true value of y lies within these limits. C is also called the level of confidence and the range (y_{upper} to y_{lower}) defines the width of the confidence band.

Usually C is taken as either 0,95 or 0,90 and the corresponding limits are called the 95 % or 90 % confidence limits respectively.

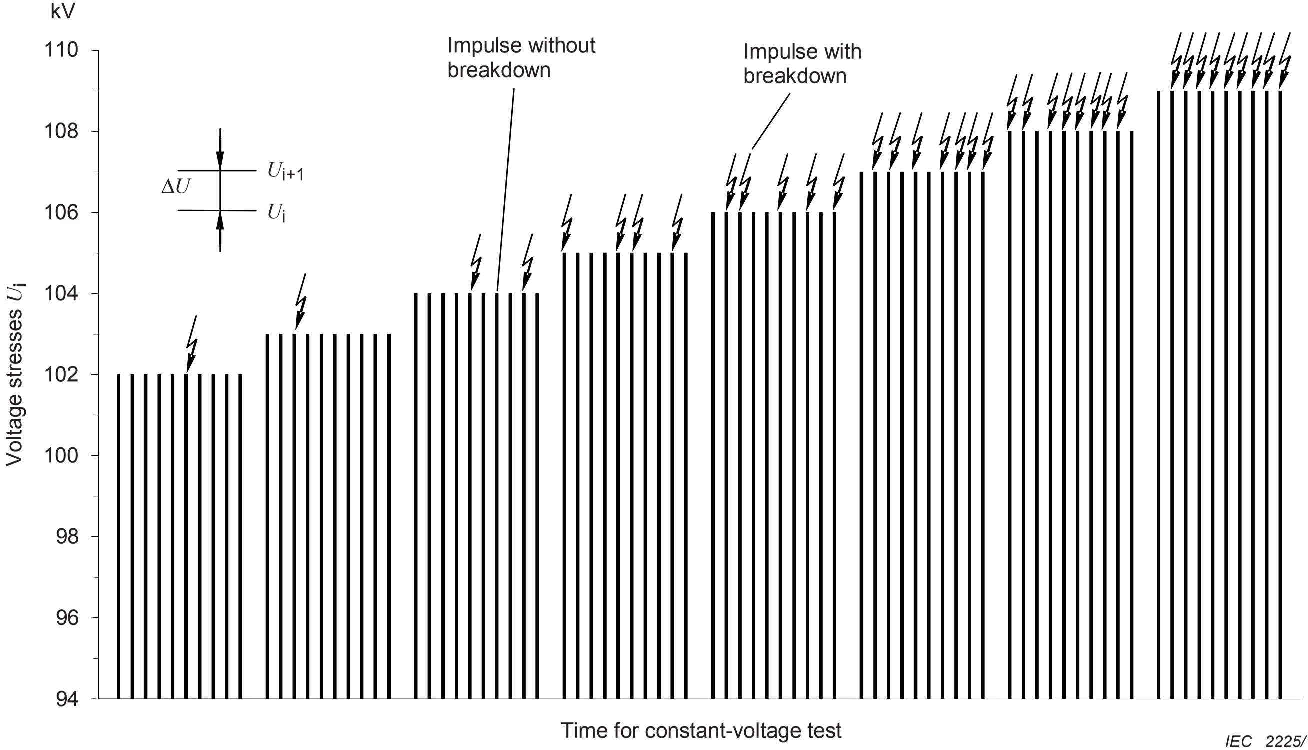
For a given C value, the width of the confidence band depends on both n and the value of the standard deviation s. The standard deviation s should be estimated when possible from tests made under realistic conditions. In general, the larger the number of tests made, the better will be the estimate of s. It should, however, be remembered that during a prolonged test series, ambient conditions may change to an extent which offsets the gain in accuracy from the increased number of tests.

Since accurate estimation of s from a limited number of tests is not possible, values estimated from the pooled results of many tests are often specified by the relevant Technical Committees.

A.3 Analysis of test results

This Clause is applicable to cases where the results of tests can be regarded as independent estimates, i.e., where a result of a test is not influenced by what may have occurred in any preceding test.

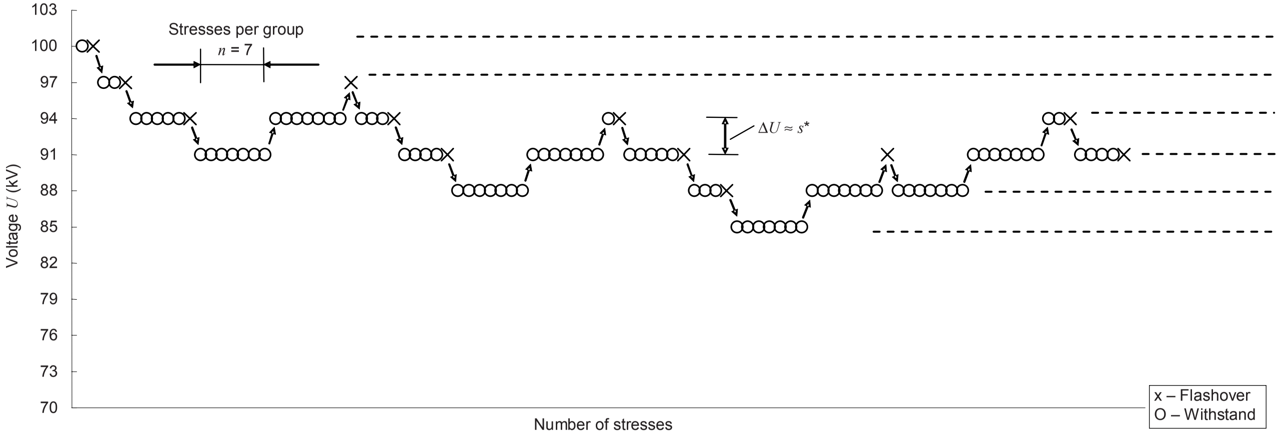
NOTE For checking the independence of a series of test results see the relevant literature [A1-A4].



IEC 2225/10

number of voltage stress, i	1	2	3	4	5	6	7	8
number of voltage applications, n_i	10	10	10	10	10	10	10	10
number of disruptive discharges, k_i	1	1	2	4	5	7	8	9
disruptive-discharge frequency, $f_i = k_i/n_i$	0,1	0,1	0,2	0,4	0,5	0,7	0,8	0,9
total disruptive discharges, g	1	2	4	8	13	20	28	37

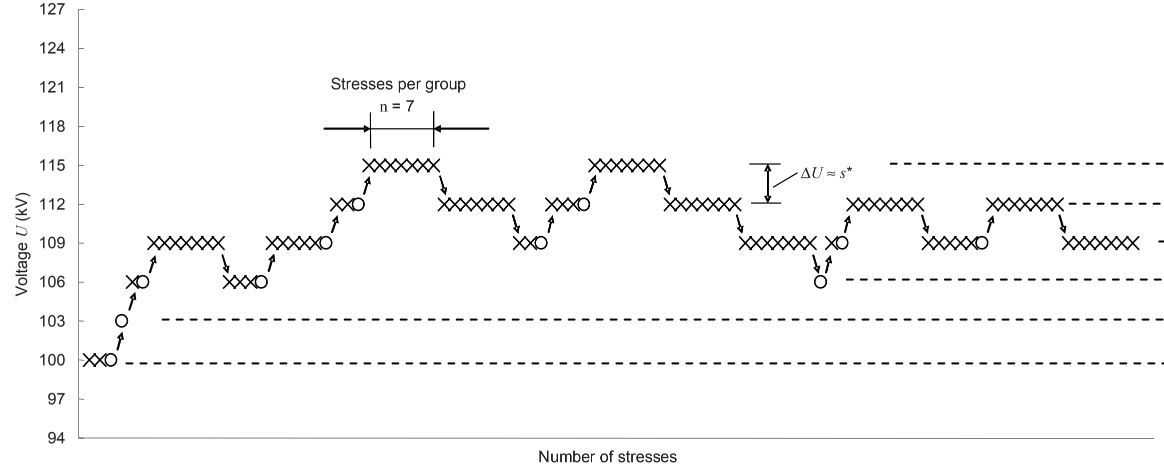
Figure A.1 – Example of a multiple-level (Class 1) test



IEC 2226/10

Number of k_j groups at u_j	Number i =1…l accepted voltages	Number k_i of accepted groups	Voltages u_i of accepted groups	Total number m of accepted groups	Term $k_i \cdot u_i$	Disruptive voltage probability at n = 7	Disruptive voltage u_p
1				18		p = 10 %	U_{10} = 91,8 kV
2	4	2	97		194		
5	3	5	94		470		
7	2	7	91		637		
4	1	4	88		352		
1			kV				

Figure A.2a – Decreasing



IEC 2227/10

Number of k_j groups at u_j	Number i =1…l accepted voltages	Number k_i of accepted groups	Voltages u_i of accepted groups	Total number m of accepted groups	Term $k_i \cdot u_i$	Disruptive voltage probability at n = 7	Disruptive voltage u_p
2	4	2	115	18	230	p = 90 %	U_{90} = 110,2 kV
6	3	6	112		672		
7	2	7	109		763		
3	1	3	106		318		
1							
1			kV				

Figure A.2b – Increasing

Figure A.2 – Examples of decreasing and increasing up-and-down (Class 2) tests for determination of 10 % and 90 % disruptive-discharge probabilities respectively

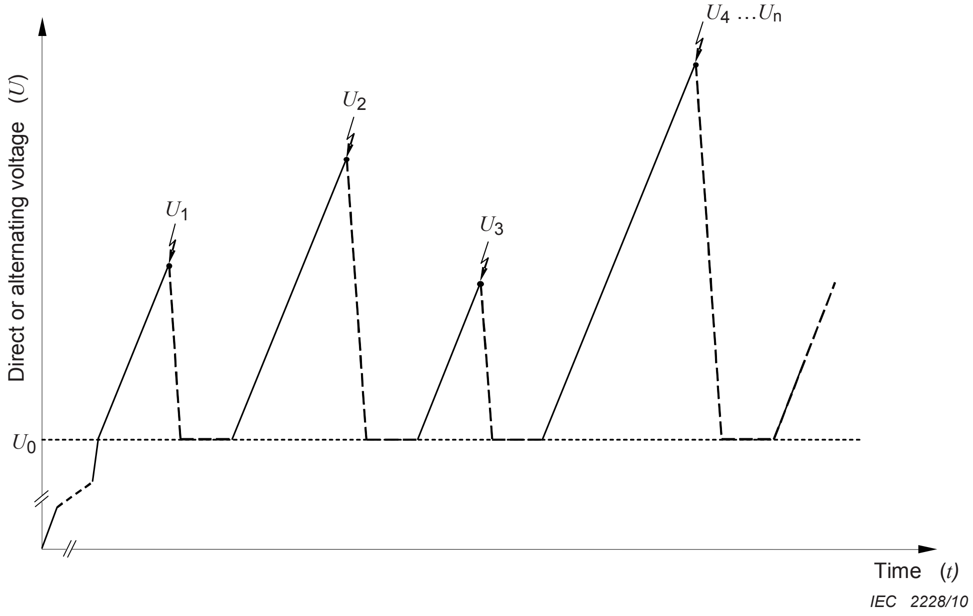


Figure A.3a – Continuous voltage increase

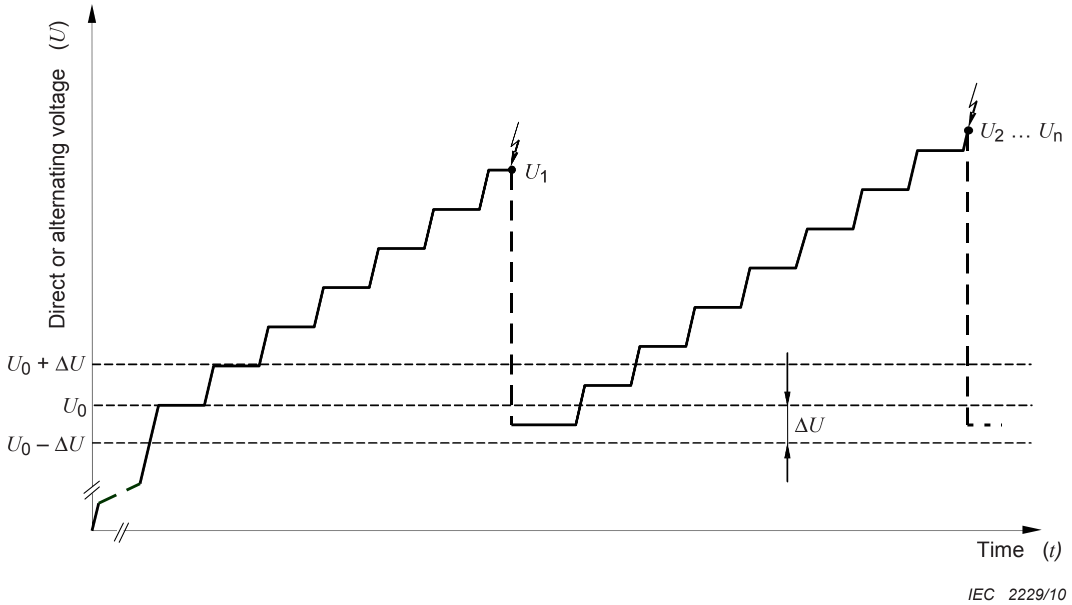


Figure A.3b – Stepwise voltage increase

Figure A.3 – Examples of progressive stress (Class 3) tests

A.3.1 Treatment of results from Class 1 tests

In this case, the discharge frequency $f_i = d_i/n_i$ at a voltage level U_i (i=1,2,...m) is taken as an estimate of $p(U_i)$, the disruptive-discharge probability at the voltage level U_i. The m estimates of $p(U_i)$ obtained in a Class 1 test can then be fitted to an assumed probability distribution function $p(U)$ and its parameters U_{50} and $s = U_{50} - U_{16} = U_{84} - U_{50}$ are determined.

This has been traditionally done by plotting f_i versus U_i on special graph paper designed to give a straight line plot when the probability estimates conform to a particular probability distribution function $p(U)$. A well-known example is Gaussian or Normal probability paper that yields a straight-line plot for estimates conforming to the Gaussian distribution function:

$$p(U) = (1/s\sqrt{2\pi}\int_{-\infty}^{U} \exp\left[-(u-U_{50})^2/2s^2\right]du$$

NOTE 1 Normal probability papers do not have ordinate scales embracing the values $p = 0$ or $p = 1$. Accordingly, tests at voltage levels always causing discharges, i.e., $d_i = n_i$, or tests at levels causing no discharges, i.e., $d_i = 0$, 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.

Currently, computer programs using analytical fitting techniques, involving the least-squares method or the maximum likelihood method (see [A4]), may be used to find U_{50}, s (as well as the parameters of other applied distribution functions) and the related confidence limits of these estimates. They contain adequate methods (such as conventional regression coefficients or confidence limits) to check if the assumed probability function fits the measured points with sufficient accuracy. For details consult the relevant literature [A1-A4].

As a general guide, the width of the confidence band tends to vary inversely with the square root of the number n_i of voltage applications at each level U_i and inversely with the number of test levels m. Note also as an example that if all values of f_i are not zero or unity, with 10 voltage applications (n_i = 10) at each of five levels (m = 5), the 95 % confidence limits would be:

For U_{50}:

$$U^*_{50} - 0{,}72s^* \le U_{50} \le U^*_{50} + 0{,}72s^*$$

and for s:

$$0{,}4\ s^* \le s \le 2{,}0\ s^*$$

where U^*_{50} and s^* are the estimates of U_{50} and s obtained by fitting the test results to an assumed discharge probability distribution function $p(U)$.

NOTE 2 The width of the confidence band tends to be smallest for estimates of U_p in the vicinity of p = 0,5 or 50 %.

A.3.2 Treatment of results from Class 2 tests

A Class 2 test provides an estimate of U_p, the voltage at which the disruptive-discharge probability is $p. U^*_p$, the estimate of U_p, is given by the following approximate formula (for a more accurate formula, see the technical literature):

$$U^*_p = \sum_{i=1}^{l}(k_i U_i)/m$$

where k_i is the number of groups of stresses each consisting of n voltage applications at the voltage level U_i and m the total number of useful groups. The appropriate value of n is given by the formulas below for a desired probability p. To avoid appreciable errors, the lowest voltage level taken into account should not differ from U^*_p by more than $2\Delta U$.

The withstand procedure described in A.1.2 provides an estimate of U_p for a disruptive-discharge probability p given by:

$$p = 1 - (0{,}5)^{1/n}$$

while the discharge procedure gives U_p for:

$$p = (0{,}5)^{1/n}$$

The values of p for which U_p can be estimated in up-and-down tests are limited by the requirement that n be an integer. Examples are given in Table A.1.

Table A.1– Discharge probabilities in up-and-down testing

n =	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 s and its confidence limits are also available but are not recommended for general use.

A.3.3 Treatment of results from Class 3 tests

The result of a Class 3 test is usually a series of n voltages U_i from which parameters U_{50} and s of a disruptive-discharge probability function are to be determined. For a Gaussian (or Normal) distribution, estimates of the parameters U_{50} and s are given by

$$U_{50}^{*} = \sum U_i / n$$

$$s^{*} = \left[\sum (U_i - U_{50}^{*})^2 / (n-1) \right]^{1/2}$$

For other distributions, the maximum likelihood methods can be employed to estimate the relevant parameters (see Clause A.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 (of U_{50}^{*} and s^{*}) 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 U_{50} and s obtained from a test with n = 20 are:

$$(U_{50}^{*} - 0{,}47 s^{*}) \le U_{50} \le (U_{50}^{*} + 0{,}47 s^{*})$$

and

$$0{,}74 s^{*} \le s \le 1{,}48 s^{*}$$

A.4 Application of maximum likelihood methods

Maximum likelihood methods may be used for the evaluation of the results of all of the above classes of tests by any type of probability function. These methods permit estimation of the parameters and hence quantiles of the breakdown voltage U_p. Furthermore, it is possible to use all the results obtained and the confidence limits corresponding to any desired confidence level C can be found. In the following only the principle is explained. See the relevant literature [A1-A4] and available software.

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 U_i are known. If the form of the disruptive-discharge probability distribution function, e. g. of $p(U; U_{50}, s)$, is assumed, the probability of a discharge at the level U_i is $p(U_\mathrm{i} ; U_{50}, s)$ and the probability of a withstand is $(1 – p(U_i ; U_{50}, s))$. The likelihood function L_i corresponding to d_i discharges and w_i withstands occurring at a voltage level U_i is then:

$$L_i = p\,(U_\mathrm{i}\,; U_{50}, s)^{d_\mathrm{i}}(1 - p\,(U_\mathrm{i}\,; U_{50}, s))^{w_\mathrm{i}}$$

As U_i, d_i and w_i are known, L_i is a function of the parameters (e. g. U_{50} and s) only.

The likelihood of a complete set of results embracing n values of U_i then becomes:

$$L = L_1 L_2 \ldots L_\mathrm{i} \ldots L_\mathrm{n} = L(U_{50}, s)$$

For Class 3 tests with stepwise increased voltage levels each voltage level U_i which appears in the results, corresponds to a disruptive discharge. In general, a voltage level U_i will appear m_i times where $m_i \geq 1$. The log-likelihood log L then becomes:

$$\log L = m_1 \log[f(U_1;U_{50},s)] + m_2 \log[f(U_2;U_{50},s)] + \ldots + m_\mathrm{n} \log[f(U_\mathrm{n};U_{50},s)]$$

where f characterizes the probability density function in the vicinity of U_i ($i = 1,\ldots n$).

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 literature.

The best estimates of the parameters (e. g. U_{50}, s) are those values (U^*_{50} and s^*) that maximise L. This shall be made by numerical methods. Related software is available.

The maxima may be found by using a computer to make iterative calculations of L for assumed parameter values (U^*_{50} and s^*). With parameter estimates fixed, U_p corresponding to any desired value of disruptive-discharge probability, p, can be found from the assumed disruptive-discharge probability distribution function. Methods for determining the confidence limits of U^*_{50} and s^* are to be found in the literature. For the case of $C = 0{,}9$ the equation $L(U_{50}; s) = 0{,}1\ L_\mathrm{max}$ permits determination of these confidence limits.

NOTE In addition to the analysis based on the Gaussian distribution (see A.3.1) the maximum likelihood method also delivers reliable results for other theoretical probability distribution functions, e.g. for the Weibull or the Gumbel distribution. For details see the relevant literature and available software.

A.5 Reference documents

[A1] CARRARA, G., and HAUSCHILD, W. *Statistical evaluation of dielectric test results*. Electra No. 133 (1990), pp. 109-131.

[A2] YAKOV, S. *Statistical analysis of dielectric test results*. CIGRE Brochure No. 66 (1991)

[A3] HAUSCHILD, W., and MOSCH, W. *Statistical Techniques for HV Engineering*. IEE Power Series No. 13, Peter Pereginus Ltd., London, 1992

[A4] VARDEMAN, S. B. *Statistics for Engineering Problem Solving*. IEEE Press/PWS Publishing Company, Boston, 1994

Annex B
(normative)

Procedures for calculation of parameters of standard lightning-impulse voltages with superimposed overshoot or oscillations

B.1 General remarks

This annex describes procedures for the calculation of parameters of all full lightning-impulse voltages, including those with superimposed overshoot. The basis is outlined in Clause B.2, the standard method on which parameter definitions are based is given in Clause B.3, and an alternative manual method is given in Clause B.4. Procedure for treatment of tail chopped impulses is given in Clause B.5.

Other methods are permitted provided the user estimates the uncertainty that the method contributes to the combined uncertainty and that the combined uncertainty is within the limits set in IEC 60060-2. The implementation of the method used shall meet the requirements of IEC 61083-2.

B.2 Basis of the procedures

The procedure is based on the empirical equation:

$$U_t = U_b + k(f)(U_e - U_b) \tag{B.1}$$

which describes the test voltage, U_t, that the insulation is subjected to, under lightning-impulse voltage with an overshoot magnitude, β.

Where

U_b is the maximum value of the base curve;

U_e, is the maximum value of the original noise free recorded curve, and the test voltage function is a frequency dependent function given by:

$$k(f) = \frac{1}{1 + 2{,}2 f^2} \tag{B.2}$$

where f is frequency in MHz.

B.3 Procedure for evaluation of parameters of full lightning impulses

This procedure is an implementation of Equation (B.1), and is used for computer aided calculation of digitally recorded impulses. The procedure is used to obtain the test voltage curve from which the impulse parameters are calculated.

The steps of the procedure are as follows:

a) find the base level of the recorded curve by calculating the mean of the voltage values from the flat part in the beginning of the record where the input voltage is zero;

b) remove the base level offset from the recorded curve, $U(t)$, to obtain the offset compensated recorded curve, $U_0(t)$, and use that curve for the remaining steps;

c) find the extreme value, U_e, of the offset compensated recorded curve, $U_0(t)$ (Figure B.1);

d) find the last sample on the front having a voltage value less than 0,2 times the extreme value, U_e;

e) find the last sample on the tail having a voltage value larger than 0,4 times the extreme value, U_e;

f) select data starting from the sample after the sample determined in step d), up to and including the sample determined in step e) for further analysis;

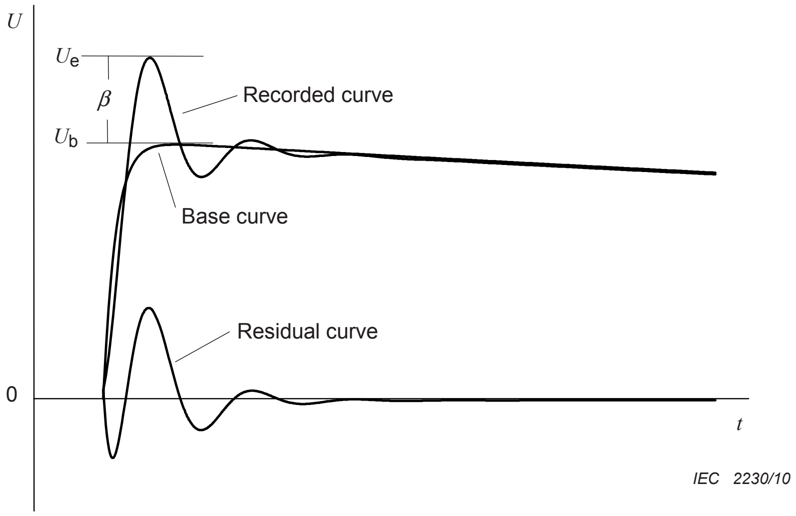


Figure B.1 – Recorded and base curve showing overshoot and residual curve

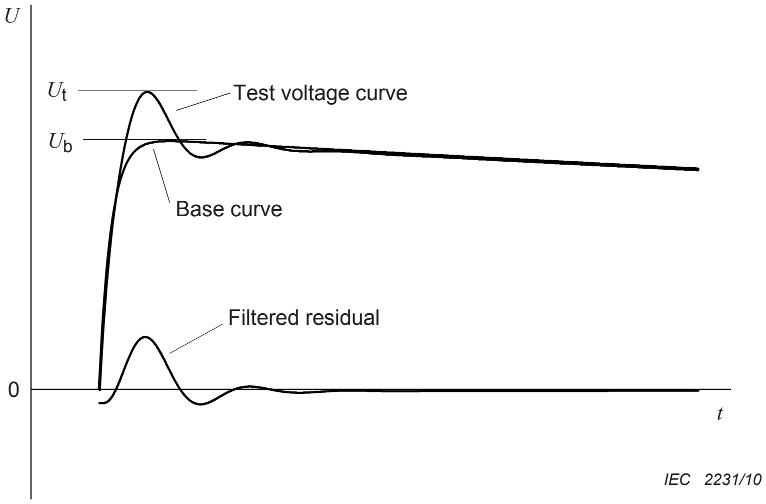


Figure B.2 – Test voltage curve (addition of base curve and filtered residual curve)

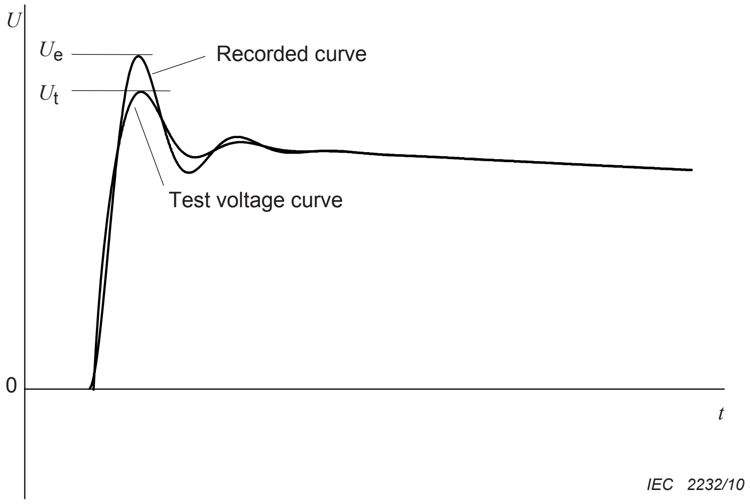


Figure B.3 – Recorded and test voltage curves

g) fit the following function to the data selected in step f) (see Clause C.1):

$$u_d(t) = U\left(e^{-\frac{(t-t_d)}{\tau_1}} - e^{-\frac{(t-t_d)}{\tau_2}}\right).$$

Here t is time, $u_\mathrm{d}(t)$ is the voltage function. U, τ_1, τ_2 and t_d are the parameters to be found by fitting[2];

h) construct the base curve, $U_\mathrm{m}(t)$, of the waveform, by using zero values for sample points up to time t_d (as calculated in step g) and values of $u_\mathrm{d}(t)$ for sample points from time t_d up to the instant of the last sample defined in step e)) (see Figure B.1);

i) subtract the base curve $U_\mathrm{m}(t)$ from the offset compensated recorded curve, $U_0(t)$ to obtain the residual curve $R(t) = U_0(t) – U_\mathrm{m}(t)$ (Figure B.2);

j) create a digital filter (see Clause C.2) with its transfer function $H(f)$ equal to that defined by the test voltage function $k(f)$ (Equation B.2);

k) apply the digital filter to the residual curve $R(t)$ to obtain the filtered residual curve $R_\mathrm{f}(t)$ (see Figure B.2);

l) add the filtered residual curve $R_\mathrm{f}(t)$ to the base curve $U_\mathrm{m}(t)$ to obtain the test voltage curve, $U_\mathrm{t}(t)$;

m) calculate the value of the test voltage, U_t, and time parameters from the test voltage curve (see Figure B.2);

n) find the maximum value U_b of the base curve $U_\mathrm{m}(t)$ (see Figure B.2);

o) calculate the relative overshoot magnitude, $\beta' = 100 \cdot \frac{U_e - U_b}{U_e}$ %;

p) display the offset compensated recorded curve, $U_0(t)$, and the test voltage curve $U_\mathrm{t}(t)$ (see Figure B.3);

q) determine and report the values of the test voltage, U_t, front time, T_1, time to half value, T_2, and relative overshoot magnitude, β'.

---

[2] U is the amplitude constant, τ_1 and τ_2 are the time constants the waveform and t_d is the time delay between the origin of the fitted curve and the triggering point of the recorded curve.

B.4 Procedure for manual calculation from graphical waveforms

This procedure is an implementation of Equation (B.1), and it is used for manual calculation of the impulse parameters from waveforms in graphical formats.

NOTE A manual evaluation will lead to less accurate results compared to the procedure for calculation from digital waveforms.

The steps of the procedure are as follows:

a) draw a base curve, $U_{\mathrm{m}}(t)$, manually through the recorded curve, $U(t)$, so as to remove oscillations on the front and peak;

b) find the maximum value of $U_{\mathrm{m}}(t)$, U_{b};

c) find the maximum value U_{e} of the recorded curve, $U(t)$;

d) calculate the duration, t, of the overshoot by finding the difference in time values at the two crossing points of $U(t)$ and $U_{\mathrm{m}}(t)$ curves on both side of the maximum peak of $U(t)$, and calculate the overshoot frequency $f_0 = 1/2t$;

e) calculate the value of test voltage function $k(f)$ from equation (B.2);

f) calculate the value of the test voltage, U_{t} using equation (B.1);

g) calculate the relative overshoot magnitude, $\beta' = 100\frac{U_e - U_b}{U_e}$ %;

h) determine the time parameters from the base curve using U_{t} as the peak voltage to determine the 30 %, 90 % and 50 % values;

i) report the value of the test voltage, U_{t}, front time, T_1, time to half value, T_2, and relative overshoot magnitude, β'.

B.5 Procedure for evaluation of parameters of tail chopped lightning impulses

This procedure is an adaptation of the algorithm given in Clause B.3 for evaluation of full lightning impulses. This procedure can be used when the chopping happens after 95 % of the extreme value level.

For this adapted procedure two records are needed:

1) The tail chopped impulse to be evaluated.
2) A full reference impulse recorded (usually) on lower voltage without changing the setup.

The procedure is as follows:

Apply steps a) to c) to both the full reference impulse and the chopped impulse:

a) find the base level of the recorded curve by calculating the mean of the voltage values from the flat part in the beginning of the record where the input voltage is zero;

b) remove the base level offset from the recorded curve, $U(t)$, to obtain the offset compensated recorded curve, $U_0(t)$, and use that curve for the remaining steps;

c) find the extreme value, U_{e}, of the offset compensated recorded curve, $U_0(t)$;

Apply steps d) to h) to the full reference impulse:

d) find the last sample on front having a voltage value less than 0,2 times the extreme value, U_{e};

e) find the last sample on the tail having a voltage value larger than 0,4 times the extreme value, U_{e};

f) select data starting from the sample after the sample determined in step d), up to and including the sample determined in step e) for further analysis;

g) fit the following function to the data selected in step f):

$$u_d(t) = U\left(e^{-\frac{(t-t_d)}{\tau_1}} - e^{-\frac{(t-t_d)}{\tau_2}} \right)$$

Here t is time, $u_\mathrm{d}(t)$ is the voltage function, and U, τ_1, τ_2 and t_d are the parameters to be found by fitting;

h) construct the base curve, $U_\mathrm{m}(t)$, of the waveform, by using zero values for sample points up to time t_d (as defined in step d) and values of $u_\mathrm{d}(t)$ for sample points from time t_d up to the instant of the last sample defined in step e;

Apply steps 1) to 7) to the tail chopped impulse:

1) find the instant of chopping;
2) find the point where the chopped waveform starts to deviate from the full reference waveform;
3) select data up to and including that point for further analysis;
4) find the time lag t_L between the records of full reference and chopped impulse (e.g. by using cross correlation techniques, or by matching the 30 %, 50 % and 80 % levels on the front);
5) adjust the time lag between full and chopped impulses to zero;
6) find the ratio E between the amplitudes of the chopped and full impulses (e.g. by dividing the peak values, or by dividing average values calculated over specified interval on both records);
7) scale the amplitude of the base curve by this factor E.

i) subtract the scaled base curve $U_\mathrm{m}(t)$ from the offset compensated recorded curve, $U_0(t)$ to obtain the residual curve $R(t) = U_0(t) - U_\mathrm{m}(t)$;

j) create a digital filter (see Annex C) with its transfer function $H(f)$ equal to that defined by the test voltage factor function $k(f)$ (Equation (B.2));

k) apply the digital filter to the residual curve $R(t)$ to obtain the filtered residual curve $R_\mathrm{f}(t)$;

l) add the filtered residual curve $R_\mathrm{f}(t)$ to the base curve $U_\mathrm{m}(t)$ to obtain the test voltage curve, $U_\mathrm{t}(t)$;

m) calculate the value of the test voltage, U_t, and time parameters from the test voltage curve;

n) find the maximum value U_b of the base curve $U_\mathrm{m}(t)$;

o) calculate the relative overshoot magnitude, $\beta' = 100 \cdot \frac{U_e - U_b}{U_e}$ %;

p) display the recorded curve $U(t)$ and the test voltage curve $U_\mathrm{t}(t)$.

q) report the value of the test voltage, U_t, front time, T_1, time to chopping, T_C, and relative overshoot magnitude, β'.

Annex C
(informative)

Guidance for implementing software for evaluation of lightning-impulse voltage parameters

C.1 Guidance for implementing base curve fitting

The function to be fitted to the recorded curve has four free parameters (U, τ_1, τ_2 and t_d):

$$u_d(t) = U\left(e^{-\frac{(t-t_d)}{\tau_1}} - e^{-\frac{(t-t_d)}{\tau_2}} \right) \tag{C.1}$$

The Levenberg-Marquardt algorithm and its derivatives have been successfully used for fitting this function on the recorded curve. The following are examples of software packages that have been used for this purpose:

Software package (tested version)	Function used for fitting
Matlab®.[3], and its Optimization toolbox (Version 7.0.4)	lqscurvefit
GNU Octave[4] (Version 3.2.0)	leasqr
LabVIEW™ [5] (LabVIEW 8 Professional)	Nonlinear Curve Fit
LabWindows™/CVI [6] (Version 6.0)	NonLinearFit

Setting the initial guess for the free parameters shortens the computation time. Initial guess given for the fitting function could be for example:

U: The extreme value of the curve

τ_1: 70µs

τ_2: 0,4µs

---

[3] MATLAB® is the trade name of a product supplied by The MathWorks, Inc.

[4] GNU Octave is freely redistributable software under GNU General Public License by John W. Eaton et. al. http://www.gnu.org/software/octave/.

[5] NI LabVIEW™ is the trade name of a product supplied by National Instruments Corporation.

[6] NI LabWindows™/CVI is the trade name of a product supplied by National Instruments Corporation.

The above information is given for the convenience of users of this standard and does not constitute an endorsement by IEC of the product named. Equivalent products may be used if they can be shown to lead to the same results.

t_d: True or virtual origin of the curve

Normalizing the data (i.e. scaling it so that both voltage and time scales span approximately from 0 to 1) has been found to improve the convergence of the algorithm. The fitted parameters then need to be scaled back to the original voltage and time scales.

The Newton-Raphson algorithm has been proven to produce results which are equal to those obtained by Levenberg-Marquardt algorithm.

C.2 An example of a digital filter for implementation of the test voltage function

For implementation of the test voltage function a digital filter with its amplitude-frequency response being equal to the test voltage function (equation B.2 in Annex B) has to be constructed. The example given here is an efficient and accurate implementation of a zero-phase Infinite Impulse Response (IIR) filter. Other filters, such as Finite Impulse Response (FIR) filters built by a frequency sampling method or window-based arbitrary response filter design algorithms and commercial software, can also be used.

A zero phase IIR filter designed by forward calculation is described in [C1]. In this approach the attenuation of the filter is only half of what is needed, but the data is passed through the filter twice, first forward and then in reverse order. This filtering gives an output that matches the test voltage function with negligible amplitude error and phase shift.

Only two filter coefficients are needed to implement the forward filter, the derived equations given in [C1] for constructing this filter are:

$$\begin{aligned} y(i) &= b_0 x(i) + b_1 x(i-1) + a_1 y(i-1) \\ b_0 &= b_1 = \frac{x}{1+x} \\ a_1 &= \frac{1-x}{1+x} \\ x &= \tan\left(\frac{\pi T_S}{\sqrt{a}}\right) \end{aligned} \tag{C.2}$$

where a equals $2{,}2\times10^{-12}$ (the -3 dB point of the K-factor filter), T_S is the sampling interval used when recording the signal, $x(i)$ is the input sample array (voltage) to the filter and $y(i)$ the output sample array of the filter.

For example, for 10 ns sampling interval this gives the following coefficients:

$a_1 = -0{,}9585113$ and $b_0 = b_1 = 0{,}02074434$

The filtering is then performed twice (once in forward and once in backward direction) using the IIR forward filter with the following difference equation:

$$y(i) = 0{,}02074434\big(x(i) + x(i-1)\big) + 0{,}9585113\, y(i-1) \tag{C.3}$$

In order to avoid numerical problems often typical for IIR filters, large enough number (in this case preferably ≥ 6) of significant digits has to be used for filter coefficients.

C.3 Reference documents

[C1] LEWIN, Paul L., TRAN, Trung N., SWAFFIELD, David J., and HÄLLSTRÖM, Jari K. *Zero Phase Filtering for Lightning Impulse Evaluation: A K-factor Filter for the Revision of IEC60060-1 and -2*. IEEE Transactions on Power Delivery, Vol. 23, No. 1, pages 3-12, January 2008.

Annex D
(informative)

Background to the introduction of the test voltage factor for evaluation of impulses with overshoot

D.1 Previous version (IEC 60060-1:1989)

In the late 1980s, most laboratories used oscilloscopes to record impulses and the amount of time taken to read oscillograms and the limits on the resolution of oscillograms set practical restrictions for the requirements that could be set for testing laboratories. The previous version of this standard (IEC60060-1:1989) classified full lightning-impulse voltages into two classes: smooth full lightning-impulse voltages and full lightning-impulse voltages with damped oscillations. In practice, all impulses have some oscillations and the user had to make a subjective judgement as to when the oscillations were such that the impulse should be treated as a full lightning-impulse voltage with damped oscillations. Full lightning-impulse voltages with damped oscillations were analysed by “drawing a mean curve through the oscillations”: the user had to make a subjective judgement as to which was the correct smooth curve. A limit on “the single peak amplitude” of 5 % of the peak value (of the impulse) was set.

The analysis depended on the duration or the frequency of the overshoot: 19.2 states:

“With some test circuits, oscillations or an overshoot may occur at the peak of the impulse, if the frequency of such oscillations is not less than 0,5 MHz or the duration of overshoot not more than 1 μs, a mean curve should be drawn and, for the purpose of measurement, the maximum amplitude of this curve is chosen as the peak value defining the value of the test voltage.”

This gave an abrupt transition but was accepted as a reasonable method for oscillograms when the overshoot was limited to 5 %. A graph of the transition is shown in Figure D.1.

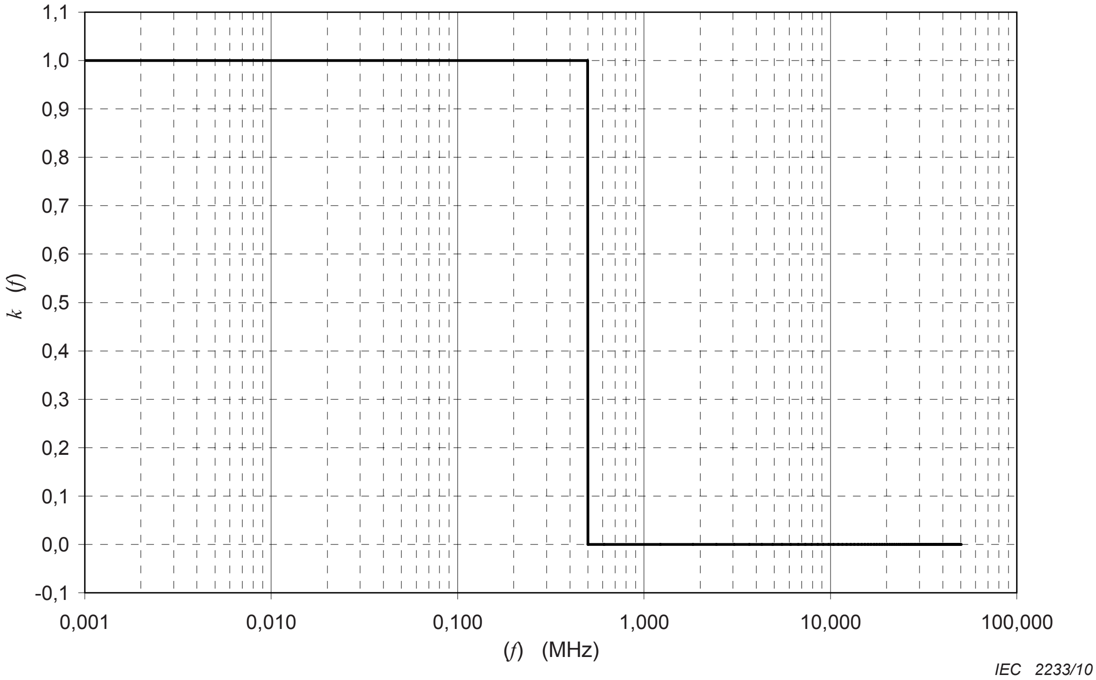


Figure D.1 – “Effective” test voltage function in IEC 60060-1:1989

This has caused three problems in the consistency of measurement:

a) The sharp transition from “maximum value” to “mean curve maximum” leads to very large errors when the frequency of the overshoot is near the transition frequency of 500 kHz. This sharp transition does not describe the behaviour of insulating materials well. It is also difficult to accurately determine the frequency.

b) The choice of the mean curve has been subjective. This contributes significant additional uncertainty in evaluating the parameters of full lightning-impulse voltages with damped oscillations.

c) It is not precisely specified how to determine if an impulse is smooth or if it has very small superimposed oscillations.

In the last two decades the use of digitizers has become widespread. Digitizers used with software analysis are capable of delivering much higher precision than oscilloscopes but their application is hindered by the imprecise specifications of IEC60060-1:1989. Users have developed a variety of software programs and these programs can be tested by waveforms of the test data generator (TDG) in IEC 61083-2 but their use for testing is still limited by the imprecise definitions of IEC 60060-1: 1989. The differences between the values of parameters calculated by a particular software program and those given in IEC 61083-2 give an additional component for the estimation of uncertainty.

D.2 Research and development to provide a solution

CIGRE WG D 1.33 (formerly known as CIGRE WG 33.03) has fostered work over the last two decades to address these problems and IEC TC 42 MT4 has been working on them from its inception.

An investigation, funded by the European Community, was conducted by 5 research institutes in the period from 1997 to 1999, on the effect of oscillations of varying frequency and amplitude superimposed on a full lightning-impulse voltage on the breakdown strength of 5 types of insulation [D1]. Breakdown voltage probability was determined for a smooth full lightning-impulse voltage whose shape was close to a sum of two exponential functions form. Breakdown voltage probability was also determined for the same impulse with superposed oscillations of varying frequency and amplitude and the voltage of the equivalent smooth full lightning-impulse voltage was found. The effect of a superimposed oscillation of frequency *f* is reduced by a factor $k(f)$ – that is, the peak value of the equivalent impulse is equal to the peak value of the applied smooth impulse plus $k(f)$ times the peak value of the oscillation. Experimentally determined values of $k(f)$ plotted against frequency are shown in Figure D.2.

Although the data for different types of insulation was quite scattered, the main conclusion was quite clear. The effect of the superimposed oscillation is frequency dependent. In other words, there is a gradual, not a sharp, transition in the frequency dependence of the overshoot magnitude on the dielectric strength.

The researchers introduced the “k-factor”, $k(f)$, to represent this gradual transition. In the standard, this is now called the test voltage function,

$$U_t = U_b + k(f)(U_e - U_b) \tag{D.1}$$

where

U_t, is the test voltage value to be determined;

U_b is the maximum value of the fitted base curve;

U_e, is the maximum value of the original recorded curve.

The test voltage value (U_t) is the maximum value of the equivalent smooth full lightning-impulse voltage. The "test voltage curve" is used to calculate the time parameters as this method is precise, reproducible, and robust. The test voltage curve is a mathematical artefact and is not the physical representation of the equivalent smooth lightning impulse. The large tolerances on the time parameters are based on decades of experience and the evidence in the European experiment also supports the fact that values of the time parameters are not very critical for determining breakdown. Hence the new estimates of the time parameters are close enough to the values that would be determined by applying the old methods.

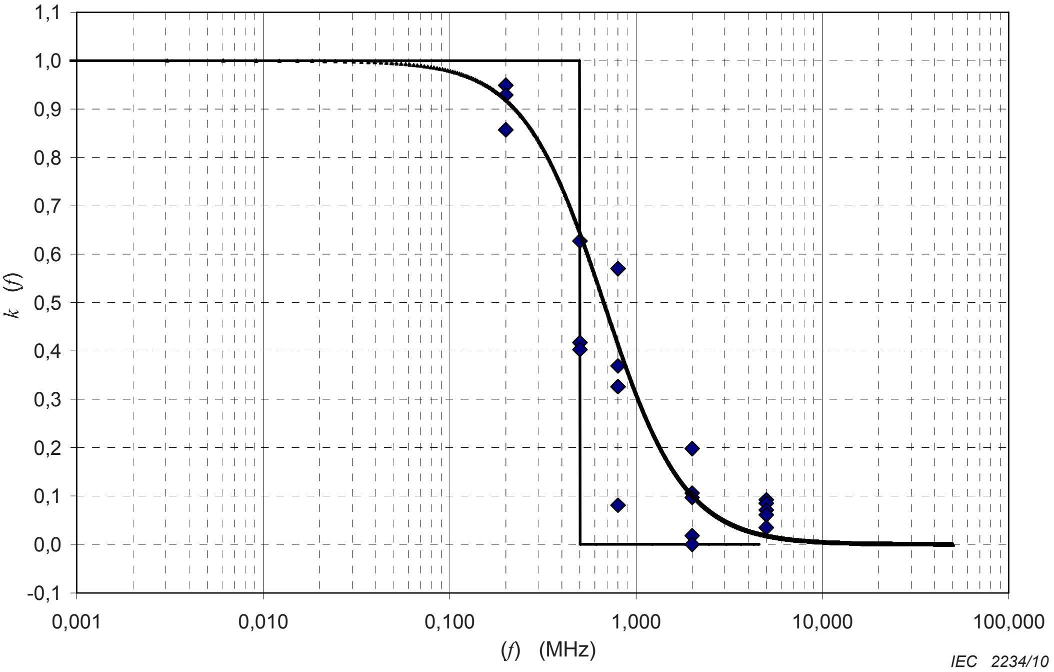


Figure D.2 – Representative experimental points from European experiments and test voltage function

There was much discussion on the most suitable formula for $k(\mathrm{f})$ within CIGRE. When it was found, by calculation, that the roll-on and roll-off frequencies did not have a large influence on the results and because they were in the extreme regions of the probable overshoot frequencies, a simple formula was proposed [D2] and was accepted for the standard. This formula is:

$$k(f) = \frac{1}{1 + 2{,}2 f^2} \qquad \text{(D.2)}$$

where f is the frequency in MHz. This is shown in Figure D.2.

Because the original data were obtained from oscillations superimposed on a full lightning-impulse voltage, the method of “residual filtering”, where the k-factor function is applied to the difference between the measured impulse and a fitted base curve, which is the sum of two exponential functions, has been used in the standard. It has been found that the choice of the two exponential functions gives good consistency for evaluation of the test voltage value but to obtain consistency in evaluations of the time parameters it has been necessary to specify the method for fitting of this function (see Annex B). Furthermore, it was found that it is convenient and mathematically valid to apply the $k(\mathrm{f})$ function as a digital filter. This enables accurate and automatic calculation of equation (D.1) without the need to determine the frequency (or frequencies) of the overshoot.

So now the three problems, mentioned in the beginning, have been solved:

a) A gradual transition function has replaced the previous sharp one. It is also not necessary to determine the frequency of the overshoot.

b) The difficulty in choosing the mean curve has been solved by the introduction of a well-defined base curve.

c) All lightning-impulse voltages are treated in the same manner so it is no longer necessary to determine if an impulse is smooth.

In addition, since the definitions are more precise and based on the defined processing of digital records, digitizers may be used with much lower uncertainties of measurement (this has been demonstrated by calculations in several laboratories during the drafting of this part of IEC 60060).

Consideration has also been given to the consistency of the results from the new procedure when other forms of distortions are present. These distortions include:

d) oscillation on the impulse front;

e) oscillation superimposed on overshoot;

f) oscillation on the tail;

g) high frequency noise.

Using the test voltage curve leads to the following consequences:

h) All high frequency noise will be removed. The oscillation on the impulse front will be removed. These are in line with the intention of the previous version of IEC 60060-1. However, other digital filters or curve fitting procedures are no longer required. Removal of these disturbances is now automatically achieved when the test voltage curve is calculated. As a consequence, the results of the impulse parameters are more consistent when these disturbances are present

i) Any low frequency variation of the waveform will be preserved. That is, the overall shape of impulse, which may be significantly different from that of the base curve, will be preserved. The base curve in this method is only an intermediate curve which is used to extract the residual curve (the oscillation). Any low frequency component of the residual curve will be preserved, which leads to the preservation of the low frequency component in the test voltage curve. This is, in principle, in line with the previous second edition of IEC 60060-1. However, the procedure in this third edition gives much more consistent results.

j) In the case of smooth impulses, only noise will be removed, the parameters of the impulse are accurately preserved.

k) In general, the same procedure should be applied to all lightning impulses (excluding front chopped).

D.3 Limit on overshoot

It is desirable to identify the limit that will be equivalent to that used in the previous version of this standard (IEC60060-1: 1989). The subjective nature of the “mean curve” leads to high uncertainties and these are estimated as 2 %. The sum of two exponential functions curve will lie below the “smooth curve” by about 3 % on average. To include nearly all (97,5 %) of the impulses with damped oscillations that were allowed by the previous version of this standard the relative overshoot is set at 10 %. This will allow the same impulses as before but allow analysis that is more precise.

NOTE In some cases (e. g. for power transformers), the overshoot cannot determine the maximum stresses on insulation, and the increase in tolerance on relative overshoot magnitude to 10 % may lead to under-testing of the equipment. This should be taken into account by the relevant Technical Committee.

D.4 Impulses outside the limit

The European study [D1] used damped oscillations with amplitudes up to about 20 % so the effects on insulation are proven. However, for general testing it should not be necessary to exceed the 10 % limit. For special cases, it is left to the relevant Technical Committee to determine the best approach. The residual curve can be used as an indicator of distortion.

It should be noted that this method is based on studies of insulation (as was IEC 60060-1:1989) and it does not consider the effects of high rates of voltage rise on the field distribution in the apparatus.

This part of IEC 60060-1 includes the definition of some new parameters (such as the extreme value and average rate of rise) recommended by the CIGRE Task Force WG 33.03 (joint activity with CIGRE SC 12).

D.5 Reference documents

[D1] GARNACHO, F., SIMON, P., GOCKENBACH, E., HACKEMACK, K., BERLIJN, S., and WERLE, P. Evaluation *of lightning-impulse voltages based on experimental results*. Electra No. 204, October 2002.

[D2] HÄLLSTRÖM, JK. et al, *Applicability of different implementations of k-factor filtering schemes for the revision of IEC60060-1 and -2*. Proceedings of the XIVth International Symposium on High Voltage Engineering, Beijing, 2005, paper B-32, p 92.

Annex E
(informative)

The iterative calculation method in the converse procedure for the determination of atmospheric correction factor

E.1 Introductory remark

It has been found that the error in the calculated atmospheric correction factor K_t is significant if K_t is significantly lower than unity (e.g., K_t=0,95 or lower) if the iterative calculation procedure (4.3.3.2) is not used. A low K_t is in most cases due to low air pressure, which is typical at high altitude test locations. The errors caused by temperatures and humidity variations are negligible.

The examples given here show that the use of the procedure (4.3.3.2) is necessary when the atmospheric pressure is significantly lower than the standard level. The examples also show that the iterative calculation procedure is normally not needed for tests carried out close to sea level.

E.2 Change of atmospheric pressure with altitude

Air pressure decreases almost linearly from sea level to an altitude up to 10 000 m above sea level. The atmospheric pressure at a given altitude can be calculated according to the following formula:

$$p = 1013 \cdot e^{-\frac{H}{8150}}$$

where p is the atmospheric pressure in hPa, H the height from sea level in metres. A plot of the air pressure p against altitude H is shown in Figure E.1. Table E.1 lists the altitudes and the normal air pressure of three locations.

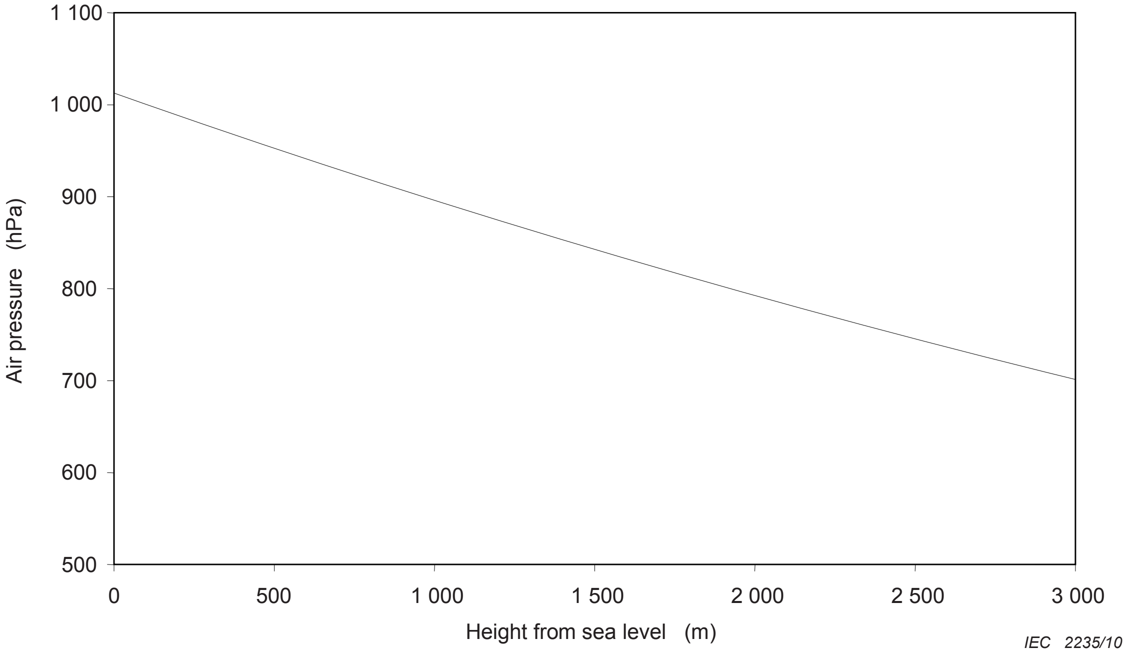


Figure E.1 – Atmospheric pressure as a function of altitude

Table E.1 – Altitudes and air pressure of some locations

Location	A	B	C
Altitude (m)	0	1 540	2 240
Air Pressure (hPa)	1 013,0	838,6	769,6

E.3 Sensitivity of K_t to U_{50}

The 50 % disruptive-discharge voltage U_{50} is an input to the calculation of the atmospheric correction factor K_t. For a 50 % disruptive-discharge test, U_{50} is the result of the test and may be used directly for the K_t calculation. Negligible error of K_t occurs due to the error of U_{50}.

However, if K_t is to be determined for correcting test voltage for a voltage withstand test, the value of U_{50} is unknown. Therefore, it is recommended in 4.3.4.3 to estimate U_{50} by multiplying the specified test voltage U_0 by 1,1, i.e.,

$$U_{50} = 1{,}1\ U_0$$

and use the estimated U_{50} for calculation of K_t.

Using the estimated U_{50} may lead to error in calculated K_t and hence the corrected test voltage $U = K_t\ U_0$.

The K_t error depends on how sensitive K_t is to the change of U_{50}, i.e., the value of the sensitivity coefficient [E1, E2] $\partial K_t/\partial U_{50}$. Numerical calculation shows that the sensitivity coefficient of K_t with respective to U_{50} is very low in the range of the air pressures close to sea level, typically an error of 5 % in U_{50} will cause less than 0,1 % error in K_t. The sensitivity coefficient increases significantly with a decrease of air pressure. At about 2 000 m above sea level, an error of 5 % in U_{50} will cause approximately 1 % error in K_t.

Table E.2 lists the initial K_t values calculated (no iterative calculation procedure applied) and its sensitivity coefficient with respect to U_{50} for a withstand test at the specified a.c. test voltage of 395 kV.

NOTE This is the a.c., r.m.s test voltage for phase-to-earth insulation of 300 kV disconnectors specified in IEC 62271-1 [E5].

Table E.2 – Initial K_t and its sensitivity coefficients with respect to U_{50} for the example of the standard phase-to-earth a.c. test voltage of 395 kV

Altitude (m)	Air pressure, *p* (hPa)	Air temperature, *T* (°C)	Relative humidity (% RH)	Discharge Length, L (m)	Initial K_t	$\partial K_t/\partial U_{50}$ (1/kV)
0	1 013,0	25,4	35	2,57	0,9904	$-4,1\times10^{-5}$
1 540	838,6	20	35	2,57	0,9308	$-2,7\times10^{-4}$
2 240	769,6	15	35	2,57	0,8849	$-4,3\times10^{-4}$

E.4 Calculation with the iterative calculation procedure

In the iterative calculation procedure, the K_t is calculated by iteration until it converges to a constant value with the residual error limit set by considering the total uncertainty budget of the test voltage.

The parameter U_{50} is used for calculating K_t (4.3.2). Take the a.c. withstand test of the 300 kV disconnector at the altitude of 2 240 m as an example (other parameters are as given in Table E.2), the first K_t value $K_{t,0}$ and the first peak test voltage value $U_{t,0}$ are calculated from the initial estimation of 50 % disruptive voltage, $U_{50,0}$, as follows:

Peak value of the specified test voltage is:

$$U_{0p} = \sqrt{2}U_0 = \sqrt{2}\times395 \text{ kV} = 558,61 \text{ kV}$$

Then,

$$U_{50,0} = 1,1U_{0p} = 1,1\times558,61 \text{ kV} = 614,48 \text{ kV}$$

$$g = \frac{U_{50,0}}{500\,L\delta k} = 0,6600$$

$$k_1 = \delta^m = 0,9069$$

$$k_2 = k^w = 0,9757$$

$$K_{t,0} = k_1k_2 = 0,8849$$

$$U_{t,0} = K_{t,0}\cdot U_{0p} = 0,8849\times558,61 \text{ kV} = 494,30 \text{ kV}$$

The calculation of $K_{t,i}$ and $U_{t,i}$ in the iteration step i uses U_{50} value obtained from the K_t value of the previous step *i-1*, $K_{t,i-1}$, i.e.,

$$U_{50,i} = 1,1\ U_{t,i-1} = 1,1\ K_{t,i-1}\cdot U_{0p}$$

The next iteration of the test voltage value $U_{t,i}$ is calculated as

$$U_{t,i} = K_{t,i}\cdot U_{0p}$$

Therefore to continue the above example, we have

$$U_{50,1} = 1,1\ U_{t,0} = 1,1\ K_{t,0}\cdot U_{0p} = 1,1\times0,8849\times558,61 \text{ kV} = 543,72 \text{ kV}$$

$$g = \frac{U_{50,1}}{500\,L\,\delta\,k} = 0{,}5840$$

$k_1 = \delta^m = 0{,}9303$

$k_2 = k^w = 0{,}9820$

$K_{t,1} = 0{,}9136$

$U_{t,1} = K_{t,1} \cdot U_{0p} = 0{,}9136 \times 558{,}61\ \text{kV} = 510{,}36\ \text{kV}$

$U_{50,2} = 1{,}1 \cdot U_{t,1} = 1{,}1 \times 510{,}36\ \text{kV} = 561{,}40\ \text{kV}$

$$g = \frac{U_{50,2}}{500\,L\,\delta\,k} = 0{,}6030$$

$k_1 = \delta^m = 0{,}9247$

$k_2 = k^w = 0{,}9805$

$K_{t,2} = 0{,}9067$

$U_{t,2} = K_{t,2} U_{0p} = 0{,}9067 \times 537{,}40\ \text{kV} = 506{,}52\ \text{kV}$

$U_{50,3} = 1{,}1 \cdot U_{t,2} = 1{,}1 \times 506{,}52\ \text{kV} = 557{,}17\ \text{kV}$

$$g = \frac{U_{50,3}}{500\,L\,\delta\,k} = 0{,}5985$$

$k_1 = \delta^m = 0{,}9261$

$k_2 = k^w = 0{,}9809$

$K_{t,3} = 0{,}9084$

$U_{t,3} = K_{t,3} U_{0p} = 0{,}9084 \times 558{,}61\ \text{kV} = 507{,}45\ \text{kV}$

$U_{50,4} = 1{,}1 \cdot U_{t,3} = 1{,}1 \times 507{,}45\ \text{kV} = 558{,}19\ \text{kV}$

$$g = \frac{U_{50,4}}{500\,L\,\delta\,k} = 0{,}5996$$

$k_1 = \delta^m = 0{,}9258$

$k_2 = k^w = 0{,}9808$

$K_{t,4} = 0{,}9080$

$U_{t,4} = K_{t,4} U_{0p} = 0{,}9080 \times 558{,}61\ \text{kV} = 507{,}22\ \text{kV}$

The difference between the test voltage peak values of the last two iterations is now

507,45 kV – 507,22 kV = 0,23 kV

which is less than 0,1 % of the test voltage peak value of the last iteration. A convergence limit of 0,1 % may be considered reasonable and is easily achievable using automation of calculation.

The error in the first estimated K_t, ΔK_t (%), and the error in the first peak test voltage, ΔU_t(%), may be calculated as

ΔK_t(%) = 100x (0,8849 – 0,9080)/0,8849 = – 2,61 %

ΔU_t(%) = 100x (494,30 – 507,22)/494,30 = – 2,61 %

The final a.c. test voltage (r.m.s value) to be applied can be then calculated from the final converged a.c. peak test voltage value, which in this example is equal to

507,22 kV / √2 = 358,66 kV

NOTE This is the test voltage to be applied at an altitude of 2 240 m for testing insulation to be used in the standard reference atmosphere (near sea level). This is not the test voltage to be applied at the standard reference atmosphere for testing the insulation to be used at the altitude of 2 240 m.

Table E.3 lists the initial and converged K_t values calculated with the iterative calculation procedure for the other altitudes with the same relative humidity and discharge length as shown in Table E.2. The errors which would result without using the iterative procedure are given in the last column. The results also show that the effect of temperature on the error is normally negligible.

Table E.3 – Initial and converged K_t values for the example of the standard phase-to-earth a.c. test voltage of 395 kV

Altitude (m)	Pressure (hPa)	Temperature (°C)	Initial K_t	Converge K_t	ΔK_t (%) or ΔU_t(%)
0	1013,0	25,4	0,9904	0,9907	– 0,03
0	1013,0	15	0.9871	0.9876	– 0,05
1540	838,6	20	0,9308	0,9404	– 1,03
1540	838,6	15	0,9272	0,9377	– 1,14
2240	769,6	20	0.8907	0,9120	– 2,39
2240	769,6	15	0,8849	0,9081	– 2,62

E.5 Comment

The error ΔK_t due to incorrect initial U_{50} input value becomes significant when the value K_t is lower than 0,95, which cannot be normally attributed to abnormal weather at sea level. A low K_t is primarily caused by testing at a high altitude location. The examples show that the error in the corrected test voltage level can be as high as 1,1 % even at an altitude of 1 500 m above sea level if the iterative calculation procedure is not used. This error increases to 2,6 % at a level of 2 240 m. At sea level, the error would normally be insignificant.

E.6 Reference documents

[E1] ISO *Guide to the expression of uncertainty in measurement*, 1995

[E2] IEC 60060-2, *High-voltage test techniques – Part 2: Measuring systems, Annex A.*

[E3] IEC 60060-3, *High-voltage test techniques – Part 3: Definitions and requirements for on-site testing.*

[E4] IEC 60071-1: 2006, *Insulation co-ordination – Part 1: Definitions, principles and rules.*

[E5] IEC 62271-1, *High-voltage switchgear and controlgear – Part 1: Common specifications*

Bibliography

[1] FESER, K. *Dimensioning of electrodes in the UHV range - Illustrated with the example of toroid electrodes for voltage dividers*. ETZ-A 96 (1975), 4 pp, 206-210.

[2] HAUSCHILD, W. *Engineering the electrodes of HV test systems on the basis of the physics of discharges in air*. 9th ISH Graz (1995), Invited Lecture 9002.

This page deliberately left blank

British Standards Institution (BSI)

BSI is the national body responsible for preparing British Standards and other standards-related publications, information and services.

BSI is incorporated by Royal Charter. British Standards and other standardization products are published by BSI Standards Limited.

About us

We bring together business, industry, government, consumers, innovators and others to shape their combined experience and expertise into standards -based solutions.

The knowledge embodied in our standards has been carefully assembled in a dependable format and refined through our open consultation process. Organizations of all sizes and across all sectors choose standards to help them achieve their goals.

Information on standards

We can provide you with the knowledge that your organization needs to succeed. Find out more about British Standards by visiting our website at bsigroup.com/standards or contacting our Customer Services team or Knowledge Centre.

Buying standards

You can buy and download PDF versions of BSI publications, including British and adopted European and international standards, through our website at bsigroup.com/shop, where hard copies can also be purchased.

If you need international and foreign standards from other Standards Development Organizations, hard copies can be ordered from our Customer Services team.

Subscriptions

Our range of subscription services are designed to make using standards easier for you. For further information on our subscription products go to bsigroup.com/subscriptions.

With **British Standards Online (BSOL)** you'll have instant access to over 55,000 British and adopted European and international standards from your desktop. It's available 24/7 and is refreshed daily so you'll always be up to date.

You can keep in touch with standards developments and receive substantial discounts on the purchase price of standards, both in single copy and subscription format, by becoming a **BSI Subscribing Member**.

PLUS is an updating service exclusive to BSI Subscribing Members. You will automatically receive the latest hard copy of your standards when they're revised or replaced.

To find out more about becoming a BSI Subscribing Member and the benefits of membership, please visit bsigroup.com/shop.

With a **Multi-User Network Licence (MUNL)** you are able to host standards publications on your intranet. Licences can cover as few or as many users as you wish. With updates supplied as soon as they're available, you can be sure your documentation is current. For further information, email bsmusales@bsigroup.com.

Revisions

Our British Standards and other publications are updated by amendment or revision.

We continually improve the quality of our products and services to benefit your business. If you find an inaccuracy or ambiguity within a British Standard or other BSI publication please inform the Knowledge Centre.

Copyright

Useful Contacts:

Customer Services
Tel: +44 845 086 9001
Email (orders): orders@bsigroup.com
Email (enquiries): cservices@bsigroup.com

Subscriptions
Tel: +44 845 086 9001
Email: subscriptions@bsigroup.com

Knowledge Centre
Tel: +44 20 8996 7004
Email: knowledgecentre@bsigroup.com

Copyright & Licensing
Tel: +44 20 8996 7070
Email: copyright@bsigroup.com

BSI Group Headquarters

389 Chiswick High Road London W4 4AL UK

...making excellence a habit.™