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IS/IEC 60060-2 (2010): High - Voltage Test Techniques, Part 2: Measuring Systems [ETD 19: High Voltage Engineering]

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उच्च-वोल्टता परीक्षण तकनीकें

भाग 2 मापन पद्धतियाँ

Indian Standard

HIGH-VOLTAGE TEST TECHNIQUES

PART 2 MEASURING SYSTEMS

ICS 17.220.20;19.080

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NEW DELHI 110002

October 2012 **Price Group 15**

High-Voltage Engineering Sectional Committee, ETD 19

NATIONAL FOREWORD

This Indian Standard (Part 2) which is identical with IEC 60060-2 : 2010 'High-voltage test techniques — Part 2: Measuring systems' issued by the International Electrotechnical Commission (IEC) was adopted by the Bureau of Indian Standards on the recommendation of the High-Voltage Engineering Sectional Committee and approval of the Electrotechnical Division Council.

The text of IEC Standard has been approved as suitable for publication as an Indian Standard without deviations. Certain conventions are, however, not identical to those used in Indian Standards. Attention is particularly drawn to the following:

a) Wherever the words 'International Standard' appear referring to this standard, they should be read as 'Indian Standard'.
b) Comma (,) has been used as a decimal marker, while in Indian Standards the current practice is to use a point (.) as the decimal marker.

In this adopted standard, reference appears to certain International Standards for which Indian Standards also exist. The corresponding Indian Standards which are to be substituted in their respective places are listed below along with their degree of equivalence for the editions indicated:

International Standard	*Corresponding Indian Standard*	*Degree of Equivalence*
IEC 60052 Voltage measurement by means of standard air gaps	IS 1876 : 2005 Voltage measurement by means of standard air gaps (*first revision*)	Identical to IEC 60052 : 2002
IEC 60060-1 High-voltage test techniques — Part 1: General definitions and test requirements	IS 2071 (Part 1) : 1993 High-voltage test techniques: Part 1 General definitions and test requirements (*second revision*)	Identical to IEC 60060-1 : 1989
IEC 61083-1 Instruments and software used for measurement in high-voltage impulse tests — Part 1: Requirements for instruments	IS 15638 (Part 1) : 2006 Instruments and software used for measurement in high-voltage impulse tests: Part 1 Requirements for instruments	Identical to IEC 61083-1 : 2001
IEC 61083-2 Instruments and software used for measurement in high-voltage impulse tests — Part 2: Evaluation of software used for the determination of the parameters of impulse waveforms	IS 15638 (Part 2) : 2006 Instruments and software used for measurement in high-voltage impulse tests: Part 2 Evaluation of software used for the determination of the parameters of impulse waveforms	Identical to IEC 61083-2 : 1996

The technical committee has reviewed the provision of the following International Standard referred in this adopted standard and has decided that it is acceptable for use in conjunction with this standard:

International Standard	*Title*
ISO/IEC Guide 98-3 : 2008	Uncertainty of measurement — Part 3: Guide to the expression of uncertainty in measurements (GUM)

Only the English language text in the International Standard has been retained while adopting it in this Indian Standard, and as such the page numbers given here are not the same as in the IEC Publication.

(*Continued on third cover*)

Indian Standard

HIGH-VOLTAGE TEST TECHNIQUES

PART 2 MEASURING SYSTEMS

1 Scope

This part of IEC 60060 is applicable to complete measuring systems, and to their components, used for the measurement of high voltages during laboratory and factory tests with direct voltage, alternating voltage and lightning and switching impulse voltages as specified in IEC 60060-1. For measurements during on-site tests see IEC 60060-3.

The limits on uncertainties of measurements stated in this standard apply to test levels stated in IEC 60071-1:2006. The principles of this standard apply also to higher levels but the uncertainty may be greater.

This standard:

- defines the terms used;
- describes methods to estimate the uncertainties of high-voltage measurements;
- states the requirements which the measuring systems shall meet;
- describes the methods for approving a measuring system and checking its components;
- describes the procedures by which the user shall show that a measuring system meets the requirements of this standard, including the limits set for the uncertainty of measurement.

2 Normative references

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

IEC 60052, *Voltage measurement by means of standard air gaps*

IEC 60060-1, *High-voltage test techniques – Part 1: General definitions and test requirements*

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 measurement in high-voltage impulse tests – Part 2: Evaluation of software used for the determination of the parameters of impulse waveforms*

ISO/IEC Guide 98-3:2008, *Uncertainty of measurement – Part 3: Guide to the expression of uncertainty in measurements (GUM)*

NOTE Further related standards, guides, etc. on subjects included in this International Standard are given in the bibliography.

3 Terms and definitions

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

3.1 Measuring systems

3.1.1
measuring system
complete set of devices suitable for performing a high-voltage measurement; software, used to obtain or calculate measuring results, also forms a part of the measuring system

NOTE 1 A measuring system usually comprises the following components:

– a converting device with the leads required for connecting this device to the test object or into the circuit and the connections to earth;

– a transmission system connecting the output terminals of the converting device to the measuring instruments with its attenuating, terminating and adapting impedances or networks;

– a measuring instrument together with any connection to the power supply. Measuring systems which comprise only some of the above components or which are based on non-conventional principles are acceptable if they meet the uncertainty requirements specified in this document.

NOTE 2 The environment in which a measuring system functions, its clearances to live and earthed structures and the presence of electric or magnetic fields may significantly affect the measurement result and its uncertainty.

3.1.2
record of performance
detailed record, established and maintained by the user, describing the measuring system and containing evidence that the requirements given in this standard have been met

NOTE This evidence includes the results of the initial performance test and the schedule and results of each subsequent performance test and performance check.

3.1.3
approved measuring system
measuring system that is shown to comply with one or more of the sets of requirements set out in this document

3.1.4
reference measuring system
measuring system with its calibration traceable to relevant national and/or international standards, and having sufficient accuracy and stability for use in the approval of other systems by making simultaneous comparative measurements with specific types of waveform and ranges of voltage

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

3.2 Components of a measuring system

3.2.1
converting device
device for converting the quantity to be measured (measurand) into a quantity, compatible with the measuring instrument

3.2.2
voltage divider
converting device consisting of a high-voltage and a low-voltage arm such that the input voltage is applied across the complete device and the output voltage is taken from the low-voltage arm

NOTE The elements of the two arms are usually resistors or capacitors or combinations of these. The device is designated by the type and arrangement of its elements (for example, resistive, capacitive or resistive-capacitive).

3.2.3
voltage transformer
converting device consisting of a transformer in which the secondary voltage, in normal conditions of use, is substantially proportional to the primary voltage and differs in phase from it by an angle which is approximately zero for an appropriate direction of the connections

[IEC 60050-321: 1986, 321-03-01]

3.2.4
voltage converting impedance
converting device which carries a current proportional to the applied voltage to be measured with a current measuring instrument

3.2.5
electric-field probe
converting device for the measurement of the amplitude and waveform of an electric field

NOTE An electric-field probe may be used to measure the waveform of the voltage producing the field provided that the measurement is not affected by corona or space charges.

3.2.6
transmission system
set of devices that transfers the output signal of a converting device to a measuring instrument

NOTE 1 A transmission system usually consists of a coaxial cable with its terminating impedance, but it may include attenuators, amplifiers, or other devices connected between the converting device and the measuring instrument. For example, an optical link includes a transmitter, an optical cable and a receiver as well as related amplifiers.

NOTE 2 A transmission system may be partially or completely included in the converting device or in the measuring instrument.

3.2.7
measuring instrument
device intended to make measurements, alone or in conjunction with supplementary devices

[IEC 60050-300: 2001, 311-03-01]

3.3 Scale factors

3.3.1
scale factor of a measuring system
factor by which the value of the measuring-instrument reading is multiplied to obtain the value of the input quantity of the complete measuring system

NOTE 1 A measuring system may have multiple scale factors for different assigned measurement ranges, frequency ranges or waveforms.

NOTE 2 For measuring systems that display the value of the input quantity directly, the nominal scale factor of the measuring system is unity.

3.3.2
scale factor of a converting device
factor by which the output of the converting device is multiplied to obtain its input quantity

NOTE The scale factor of a converting device may be dimensionless (for example, the ratio of a divider) or may have dimensions (for example, the impedance of a voltage converting impedance).

3.3.3
scale factor of a transmission system
factor by which the output of a transmission system is multiplied to obtain its input quantity

3.3.4
scale factor of a measuring instrument
factor by which the instrument reading is multiplied to obtain its input quantity

3.3.5
assigned scale factor
F
scale factor of a measuring system determined at the most recent performance test

NOTE A measuring system may have more than one assigned scale factor; for example, it may have several ranges and/or nominal epochs, each with a different scale factor.

3.4 Rated values

3.4.1
operating conditions
specified ranges of conditions under which a measuring system will operate within the specified uncertainty limits

3.4.2
rated operating voltage
maximum level of voltage of specified frequency or waveform at which a measuring system is designed to be used

NOTE The rated operating voltage may be higher than the upper limit of the assigned measurement range.

3.4.3
assigned measurement range
range of voltage of specified frequency or waveform, characterized by a single scale factor, in which a measuring system may be used

NOTE 1 The limits of the assigned measurement range are chosen by the user and verified by the performance tests specified in this standard.

NOTE 2 A measuring system can have more than one assigned measurement range with different scale factors.

3.4.4
assigned operating time
longest time during which a measuring system for direct or alternating voltages can operate at the upper limit of the assigned measurement range

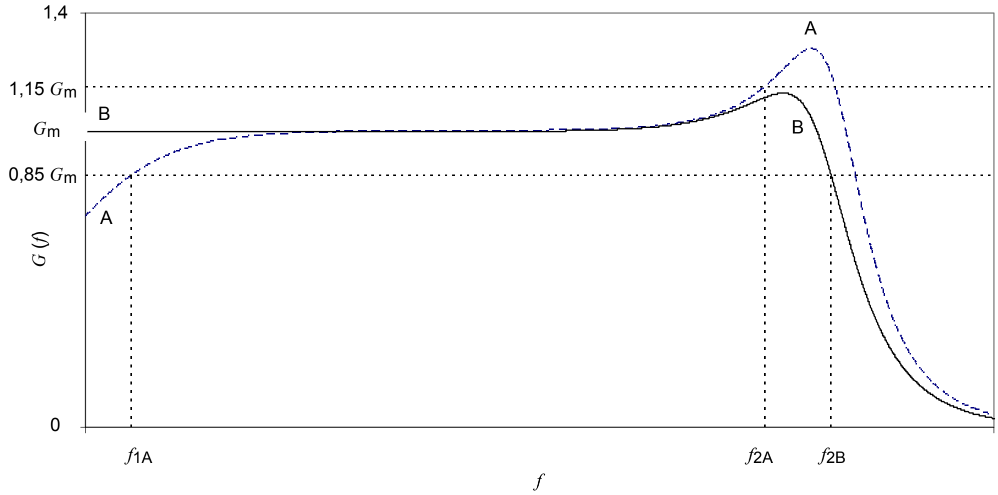
3.4.5
assigned rate of application
highest rate of specified voltage impulses for a specified time interval, at which the measuring system can operate at its upper limit of the assigned measurement range

NOTE The rate is usually given as applications per minute and the time interval in minutes or hours.

3.5 Definitions related to dynamic behaviour

3.5.1
response of a measuring system,
G
output, as a function of time or frequency, when a specified voltage is applied to the input of the system

3.5.2
amplitude-frequency response,
G(f)
ratio of the output to the input of a measuring system as a function of frequency f, when the input is sinusoidal (see Figure 1)



NOTE Lower and upper limit frequencies are shown on curve A.

Curve B shows a constant response down to direct voltage.

Figure 1 – Amplitude-frequency response with examples for limit frequencies (f_1; f_2)

3.5.3
step response,
G(t)
output of a measuring system as a function of time when the input is a step function

NOTE For more information on step response and step-response parameters see Annex C.

3.5.4
nominal epoch (impulse voltage only),
τ_{N1}
range of values between the minimum (t_{min}) and the maximum (t_{max}) of the relevant time parameter of impulse voltage for which the measuring system is to be approved

NOTE 1 The relevant time parameter is:

- the front time T_1 for full and tail-chopped lightning impulses
- the time to chopping T_c for front-chopped impulses
- the time to peak T_p for switching impulses

NOTE 2 A measuring system may have one, two or more nominal epochs for different waveforms. For example, a particular measuring system might be approved:

- for full and tail-chopped lightning impulses with an assigned scale factor F_1 over a nominal epoch τ_{N1} from T_1 = 0,8 µs to T_1 = 1,8 µs, even though the tolerance is 0,84 µs to 1,56 µs;
- or front-chopped lightning impulses with an assigned scale factor F_2 over a nominal epoch τ_{N2} from T_c = 0,5 µs to T_c = 0,9 µs;
- for switching impulses with an assigned scale factor F_3 over a nominal epoch τ_{N3} from T_p = 150 µs to T_p = 500 µs.

NOTE 3 "Front-chopped impulse" is used to designate a chopped impulse with a time to chopping that falls in the range 0,5 µs to the time of the extreme value. This is to be distinguished from a "tail-chopped impulse" which has a time to chopping greater than the time of the extreme value.

3.5.5
limit frequencies,
f_1 and f_2
lower and upper limits of the range within which the amplitude-frequency response is nearly constant (Figure1)

NOTE These limits are where the response first deviates by a certain amount (e.g. plus/minus 15 %) from the constant value. The permissible deviation should be related to acceptable uncertainties of a measuring system.

3.6 Definitions related to uncertainty

3.6.1
tolerance
permitted difference between the measured value and the specified value

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

NOTE 2 The measured test voltage is required to lie within the stated tolerance of the specified test level.

3.6.2
error
measured quantity value minus a reference quantity value

[ISO/IEC Guide 99 (VIM 2.16)]

3.6.3
uncertainty (of measurement)
parameter, associated with the result of a measurement, that characterises the dispersion of the values that could reasonably be attributed to the measurand

[IEC 60050-300: 2001, 311-01-02]

NOTE 1 Uncertainty is positive and given without sign.

NOTE 2 Uncertainty of voltage measurement should not be confused with the tolerance of a specified test voltage.

NOTE 3 For more information see Annexes A and B.

3.6.4
standard uncertainty,
u
uncertainty of the result of a measurement expressed as a standard deviation

[ISO/IEC Guide 98-3 (GUM 2.3.1)]

NOTE 1 The standard uncertainty associated with an estimate of a measurand has the same dimension as the measurand.

NOTE 2 In some cases, the relative standard uncertainty of a measurement may be appropriate. The relative standard uncertainty of measurement is the standard uncertainty divided by the measurand, and is therefore dimensionless.

3.6.5
combined standard uncertainty,
u_c,
standard uncertainty of the result of a measurement when that result is obtained from the values of a number of other quantities, equal to the positive square root of a sum of terms, the terms being the variances or covariances of these other quantities weighted according to how the measurement result varies with changes in these quantities

[ISO/IEC Guide 98-3 (GUM 2.3.4)]

3.6.6
expanded uncertainty,
U
quantity defining an interval about the result of a measurement that may be expected to encompass a large fraction of the distribution of values that could reasonably be attributed to the measurand

[ISO/IEC Guide 98-3 (GUM 2.3.5)]

NOTE 1 Expanded uncertainty is the closest match to the term “overall uncertainty” used in earlier editions of this standard.

NOTE 2 The true, but unknown test-voltage value may lie outside the limits given by the uncertainty because the coverage probability is < 100 % (see 3.6.7).

3.6.7
coverage factor,
k
numerical factor used as multiplier of the combined standard uncertainty in order to obtain an expanded uncertainty

[ISO/IEC Guide 98-3 (GUM 2.3.6)]

NOTE For 95 % coverage probability and normal (Gaussian) probability distribution the coverage factor is approximately k = 2.

3.6.8
type A evaluation
method of evaluation of a standard uncertainty by statistical analysis of a series of observations

3.6.9
type B evaluation
method of evaluation of a standard uncertainty by means other than statistical analysis of a series of observations

3.6.10
traceability
property of the result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons, all having stated uncertainties

[IEC 60050-300: 2001, 311-01-15]

3.6.11
National Metrology Institute
institute designated by national decision to develop and maintain national measurement standards for one or more quantities

3.7 Definitions related to tests on measuring systems

3.7.1
calibration
set of operations that establishes, by reference to standards, the relationship which exists, under specified conditions, between an indication and a result of a measurement

[IEC 60050-300: 2001, 311-01-09]

NOTE The determination of the scale factor is included in the calibration.

3.7.2
type test
conformity test made on one or more items representative of the production

[IEC 60050-151: 2001, 151-16-16]

NOTE For a measuring system, this is understood as a test performed on a component or on a complete measuring system of the same design to characterize it under operating conditions.

3.7.3
routine test
conformity test made on each individual item during or after manufacture

[IEC 60050-151: 2001, 151-16-17]

NOTE This is understood as a test performed on each component or on each complete measuring system to characterize it under operating conditions.

3.7.4
performance test
test performed on a complete measuring system to characterize it under operating conditions

3.7.5
performance check
simple procedure to ensure that the result of the most recent performance test is still valid

3.7.6
reference record (impulse measurements only)
record taken under specified conditions in a performance test and retained for comparison with records to be taken in future tests or checks under the same conditions

NOTE Reference records are often called “fingerprints” and used as characteristics of dynamic behaviour. In impulse voltage measurements they are usually taken from step response measurements (Annex C).

4 Procedures for qualification and use of measuring systems

4.1 General principles

Every approved measuring system shall undergo initial testing, followed by performance tests (periodic, see 4.2) and performance checks (periodic, see 4.3) throughout its service life. The initial tests consist of type tests (performed on a component or system of the same design) and routine tests (performed on every component or system).

The performance tests and checks shall prove that the measuring systems can measure the intended test voltages within the uncertainties given in this standard, and that the measurements are traceable to national and/or international standards of measurement. The system is approved only for the arrangements and operating conditions included in its record of performance.

A major requirement for a converting device, a transmission system, and a measuring instrument used in a measuring system is stability within the specified range of operating conditions so that the scale factor of the measuring system remains constant over long periods.

The assigned scale factor is determined in the performance test by calibration. The user shall apply tests given in this standard to qualify their measuring system(s). Alternatively, any user may choose to have the performance tests made by a National Metrology Institute or by a Calibration Laboratory accredited for the quantity to be calibrated. In all cases, the user shall include the test data into the record of performance.

Any calibration shall be traceable to national and/or international standards. The user shall ensure that any self-made calibration is performed by competent personnel using reference measuring systems and suitable procedures.

NOTE Calibrations performed by a National Metrology Institute, or by a laboratory accredited for the quantities calibrated and reported under the accreditation, are considered traceable to national and/or international standards.

4.2 Schedule of performance tests

To maintain the quality of a measuring system, its assigned scale factor(s) shall be determined by periodic performance tests. The interval between performance tests shall be based on evaluation of past stability of the measuring system. It is recommended that the performance test should be repeated annually, but the maximum interval shall not be longer than five years.

NOTE Long intervals between performance tests can increase the risk of an undetected change in the measurement system.

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

When a performance test is required because a performance check shows that the assigned scale factor is no longer valid, the cause of this change shall be investigated before the performance test is made.

4.3 Schedule of performance checks

Performance checks shall be made at intervals based on the recorded stability of the measuring system as shown in the record of performance. The interval from the last performance test or the last performance check shall not be longer than one year.

For a new or repaired measuring system, performance checks shall be made at short intervals to demonstrate its stability.

No reference method is identified for the performance checks because the required accuracy is less than that required for performance tests.

4.4 Requirements for the record of performance

4.4.1 Contents of the record of performance

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

The record of performance shall comprise at least the following information:

- General description of the measuring system.
- Results of type and routine tests on the converting device, transmission system(s) and measuring instrument(s) and, if performed, on the measuring system.
- Results of subsequent performance tests on the measuring system.
- Results of subsequent performance checks on the measuring system.

NOTE The general description of the measuring system usually comprises main data and capabilities of the measuring system, such as the rated operating voltage, waveform(s), range(s) of clearances, operating time, or maximum rate of voltage applications. For many measuring systems, information on the transmission system as well as high-voltage and ground-return arrangements are important. If required, a description is also given of the components of the measuring system, including for example the type and identification of the measuring instrument.

4.4.2 Exceptions

For measuring systems or components manufactured before the date of issue of the second edition of IEC60060-2, i.e. 1994, the required evidence may not be available for some part(s) of the type and routine test. Then performance tests and checks made in accordance with earlier versions of this standard are deemed adequate provided they show the scale factor is stable. The results of these previous checks shall also be entered in the record of performance.

Approved measuring systems comprising several pieces of equipment used inter-changeably may be covered by a single record of performance including all the combinations possible with the least amount of duplication possible. Specifically, each converting device shall be covered individually, but transmission systems and measuring instruments may be covered generically.

4.5 Operating conditions

A measuring system shall be connected directly to the terminals of the test object, or in such a way that the voltage difference between test object terminals and the measuring system is negligible. The parasitic coupling between the test and measuring circuit should be minimized.

NOTE 1 Parasitic coupling may need to be investigated.

An approved measuring system shall have an uncertainty within the specifications of this standard throughout the ranges of operating and environmental conditions given in the record of performance.

The assigned operating time for measuring systems for direct and alternating voltage shall be specified.

NOTE 2 The recommended minimum value for the assigned operating time is 1 h.

The maximum rate of application for impulse voltages shall be specified.

NOTE 3 The recommended minimum value for the maximum rate of application is one or two impulses/min and to be specified depending on the size of the converting device.

The range of environmental conditions, under which the components of the measuring system fulfil the requirements of this standard, shall be stated.

4.6 Uncertainty

The uncertainty of all measurements made under this International Standard shall be evaluated according to ISO/IEC Guide 98-3.

Procedures for evaluating uncertainties have been selected from ISO/IEC Guide 98-3 and presented in this standard. These simplified procedures of clause 5 are considered sufficient for the instrumentation and measurement arrangements commonly used in high-voltage testing: however, users may select other appropriate procedures from ISO/IEC Guide 98-3, some of which are outlined in Annex A and Annex B.

In general, the measurand to be considered is the scale factor of the measuring system, but in some cases other quantities, such as the time parameters of an impulse voltage and their associated errors, should also be considered.

NOTE 1 Other measurands for specific converting devices are in common use. For example, a voltage divider is characterized by the voltage ratio and its uncertainty in the assigned measurement ranges used. A voltage transformer is characterized by the ratio error, the phase displacement and the corresponding uncertainties.

According to the ISO/IEC Guide 98-3, the uncertainty of a measurement is determined by combining the uncertainty contributions of Type A and Type B (see 5.10, 5.11 and Annex A). The contributions are obtained from measurement results, from manufacturers' handbooks, calibration certificates and from estimating reasonable values of the influence quantities during the measurement. For example influence quantities mentioned in clause 5 include temperature and proximity effects. Others, like limited resolution of the measuring instrument, may be added if necessary.

NOTE 2 The resolution of a measuring instrument, e.g. one with few significant digits, may be a significant source of uncertainty.

During the actual voltage test, it is usually necessary to consider additional influencing quantities, apart from the calibration uncertainty of the scale factor stated in the calibration certificate, in order to obtain the uncertainty of measurement of the test voltage value.

Some guidance on determining uncertainty contributions, that need to be considered, and on their combination is given in Clause 5 and Annexes A and B. The uncertainty shall be given as the expanded uncertainty for a coverage probability of approximately 95 % corresponding to a coverage factor k=2 under the assumption of a normal distribution.

NOTE 3 In this International Standard, the uncertainties of the scale factor and of voltage measurement (5.2 to 5.10) are expressed by the relative uncertainties instead of the absolute uncertainty normally considered in the ISO/IEC Guide 98-3. The direct application of the ISO/IEC Guide 98-3 and consideration of the absolute uncertainties are shown in 5.11 for time parameters as well as in Annexes A and B.

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

5.1 General requirements

The assigned scale factor of the measuring system shall be determined by calibration according to the specified performance tests. The assigned scale factor is a single value for the assigned measurement range. If necessary, several assigned measurement ranges with different scale factors may be defined.

For an impulse measuring system, the performance tests also show that its dynamic performance is adequate for the specified measurements and that the level of any interference is less than the specified limits.

Due to the large size of the equipment and the real environmental conditions, the calibration should preferably be performed on site by comparison with a reference measuring system.

Smaller size measuring systems or their components may be transported to another laboratory for calibration in an arrangement that simulates the operating conditions, provided that the interference test, when specified, is performed in the test facility of the user.

If a converting device is sensitive to proximity effects, the range of clearances where the assigned scale factor is valid shall be determined and entered in the record of performance. One or more ranges of clearances and respective scale factors may be assigned.

The scale factor of a measuring system shall be determined in the assigned measurement range, preferably by comparison with a reference measuring system. However, as reference measuring systems are not always available at higher voltages, the comparison may be made at voltages as low as 20 % of the assigned measurement range, provided that linearity has been determined from this point up to the limit of the assigned measurement range. One of the methods given in 5.3 shall be used for this extension.

All equipment used in establishing the scale factors of measuring systems shall have calibrations traceable to national and/or international standards.

NOTE Calibrations performed by a National Metrology Institute, or by a laboratory accredited for the quantities calibrated and reported under the accreditation, are considered traceable to national and/or international standards.

Conditions significant for the result of the calibration of the approved measuring system shall be included in the record of performance.

5.2 Calibration – Determination of the scale factor

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

5.2.1.1 Comparison measurement

Scale factor(s) is (are) determined for a complete measuring system by comparison with a reference measuring system.

The input voltage used for calibration should be of the same type, frequency or waveform as voltages to be measured. If this condition is not fulfilled, the related uncertainty contributions shall be estimated.

For the comparison, a reference measuring system, traceable to a National Metrology Institute, shall be connected in parallel with the measuring system to be calibrated. Care shall be taken to avoid ground loops between the converting device(s) and measuring instrument(s). Simultaneous readings shall be taken on both systems. The value of the input quantity obtained for each measurement by the reference measuring system is divided by the corresponding reading of the instrument in the system under test to obtain a value F_{i} of its scale factor. The procedure is repeated *n* times to obtain the mean value F_{g} of the scale factor of the system under test at one voltage level U_{g}. The mean value is given by:

$$F_{\mathrm{g}} = \frac{1}{n}\sum_{i=1}^{n} F_{i,g}$$

The relative standard deviation s_{g} of F_{g} is given by:

$$s_g = \frac{1}{F_g}\sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(F_{i,g} - F_{\mathrm{g}})^2}$$

and the Type A relative standard uncertainty u_{g} of the mean value F_{g} is given by (Annex A):

.

$$u_{\mathrm{g}} = \frac{s_g}{\sqrt{n}}$$

NOTE 1 Usually no more than *n* = 10 independent readings are necessary.

NOTE 2 For measurement of direct and alternating voltages, independent readings should be obtained either by applying the test voltage and taking *n* readings or by applying the test voltage *n* times and taking a reading each time. For impulses, *n* impulses are applied.

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

The scale factor shall be determined over the assigned measurement range by one of the following methods described in 5.2.1.2 (preferred), 5.2.1.3 and 5.2.2.

5.2.1.2 Comparison over the full assigned measurement range

This test includes both the determination of the assigned scale factor and the determination of linearity. The scale factor determination shall be made by direct comparison with a reference measuring system at the minimum and maximum levels of the assigned measurement range and on at least three approximately equally spaced intermediate levels (Figure 2). The assigned scale factor F is taken as the mean value of all scale factors F_g recorded at h voltage levels:

$$F = \frac{1}{h}\sum_{g=1}^{h} F_g \quad \text{for } h \geq 5$$

The standard uncertainty of the determination of the assigned scale factor F is obtained as the largest of the single standard uncertainties of type A (Figure 3):

$$u_A = \max_{g=1}^{h} u_g \,.$$

The effect of a non-linearity in F is estimated as a Type B standard uncertainty expressed by

$$u_{B0} = \frac{1}{\sqrt{3}} \max_{g=1}^{h} \left| \frac{F_g}{F} - 1 \right| .$$

NOTE 1 A rounded value F_o may be taken as the assigned scale factor if the difference between F_o and F is introduced as an uncertainty contribution of Type B in the estimate of the expanded uncertainty of the scale factor F_o.

NOTE 2 The individual scale factors and their uncertainties at the h voltage levels should be given in the calibration certificate.

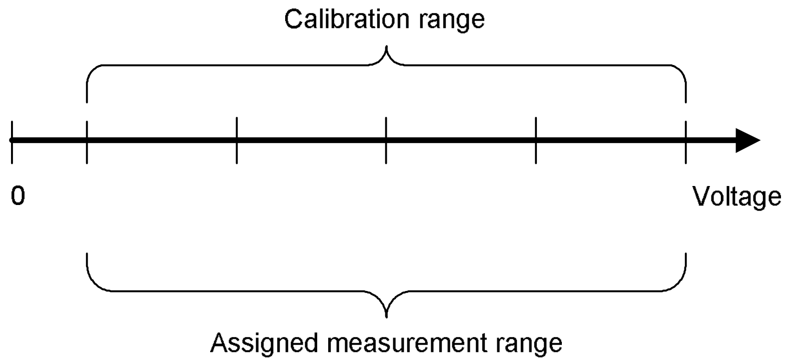


Figure 2 – Calibration by comparison over the full voltage range

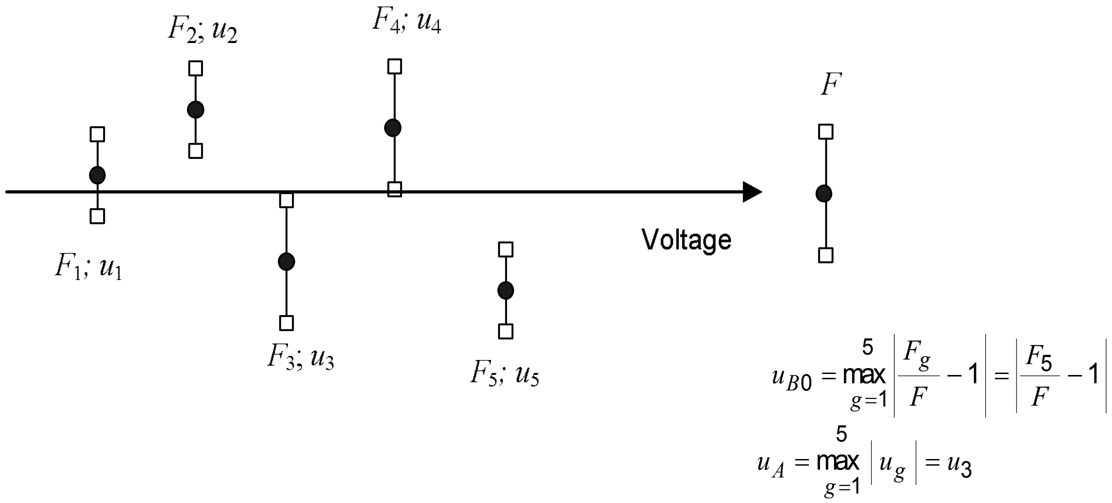


Figure 3 – Uncertainty contributions of the calibration (example with minimum of 5 voltage levels)

5.2.1.3 Comparison over limited voltage range

In cases where the assigned measurement range exceeds the capability of the reference measuring system, the scale factor shall be determined by comparison up to the maximum voltage of the reference measuring system. The comparison shall always be carried out at a voltage that is not lower than 20 % of the upper limit of the assigned measurement range (Figure 4).

The comparison shall be complemented by a linearity test in accordance with 5.3. The uncertainty contribution related to linearity shall be considered in the calculation of measurement uncertainty when using the measuring system, see 5.10.3.

The comparison with the reference measuring system is carried out at $a \geq 2$ voltage levels, where the highest voltage level is equal to the maximum voltage of the reference measuring system. The necessary linearity test is carried out at $b \geq 2$ voltage levels, with one level equal to the maximum level of comparison (see 5.3). The voltage levels shall further be chosen such that they comprise at least the minimum and the maximum levels of the assigned measurement range, and that

$$a + b \geq 6$$

The assigned scale factor F is taken as the mean value of the scale factors recorded with the reference measuring system:

$$F = \frac{1}{a} \sum_{g=1}^{a} F_g$$

The standard uncertainty Type A of the scale factor F_m is obtained as the largest of the single standard uncertainties u_g

$$u_A = \max_{g=1}^{a} u_g$$

and a non-linearity contribution for the calibration values

$$u_{B0} = \frac{1}{\sqrt{3}} \max_{g=1}^{a} \left| \frac{F_g}{F} - 1 \right| .$$

NOTE A rounded value F_o may be taken as the assigned scale factor if the difference between F_o and F is introduced as an uncertainty contribution of Type B in the estimate of the expanded uncertainty of the scale factor F_o.

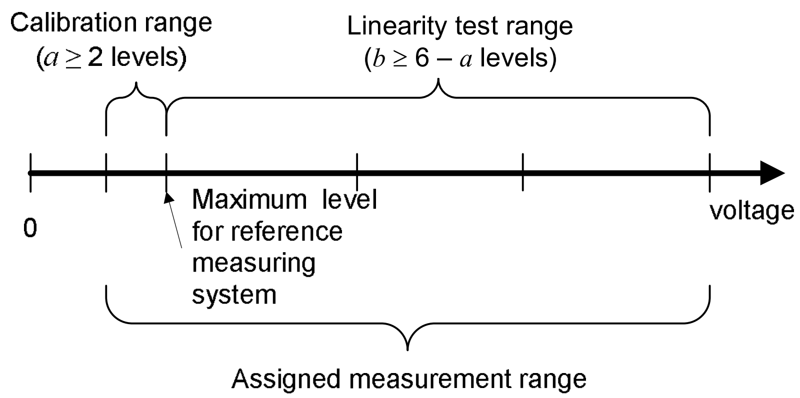


Figure 4 – Calibration by comparison over a limited voltage range, with an additional linearity test

5.2.2 Determination of the scale factor of a measuring system from the scale factors of its components (alternative method)

The assigned scale factor of the measuring system shall be determined as the product of the scale factors of its converting device, its transmission system, any secondary attenuator, and its measuring instrument.

For the converting device and the transmission system or their combination, the scale factor shall be measured by one of the methods given below. Separate tests are not required for transmission systems that consist only of cables. The scale factor of a measuring instrument is determined according to the relevant standard (see e.g. IEC 61083-1 and IEC 61083-2) or by performing a calibration and testing according to this Clause 5.

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

- comparison with a reference component (e.g. a voltage divider compared with a reference voltage divider) or the application of a precise low-voltage calibrator;
- simultaneous measurements of its input and output quantities;
- a bridge method or precise low-voltage ratio measurement;
- calculation based on measured impedances.

NOTE 1 Care should be taken to ensure that the appropriate "stray" capacitance or coupling and the mutual influence of the components are included in the measurement.

For each component of the measuring system the Type A and Type B contributions to uncertainty shall be estimated (5.2 to 5.9) and the combined uncertainty for each component shall be determined (5.10) taking into account the uncertainty contributions of the measuring devices used for the calibrations.

NOTE 2 Estimation of contributions to uncertainty in the component calibration method requires analysis of each component over the full range of conditions, - voltage, temperature, proximity effect, etc. – that may influence the result. This analysis is complex and requires deep understanding of the measurement process.

The expanded uncertainty of voltage measurement is obtained by combining these combined uncertainties of the components according to the provisions of the ISO/IEC Guide 98-3 (see also Annexes A and B, especially Example B.2).

Estimation of uncertainty of time parameter measurement shall be made applying the provisions of 5.11 and the same principles as for voltage measurement.

5.3 Linearity test

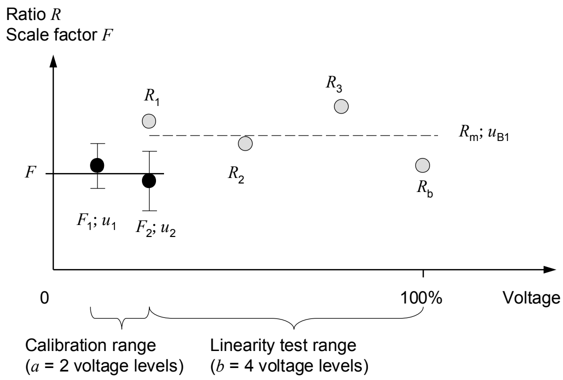
5.3.1 Application

The test is only intended to provide an extension of the validity of the scale factor from the maximum voltage at which a calibration according to 5.2.1.3 has been carried out, up to the upper limit of the assigned measurement range (Fig. 4).

The output of the measuring system shall be compared with a device or system that has proven its linearity or can be presumed to be linear over the full voltage range (see 5.3.2). Failure to prove the linearity using such a method does not necessarily mean the measuring system is non-linear. In this case another method suitable for the linearity test shall be chosen. The ratio of the reading between the measuring system and the comparison device or system, shall be established as described in 5.2.1.1 for *b* different voltages ranging from the upper limit of the assigned measurement range down to a voltage at which the scale factor has been determined (Figure 4).

Evaluation of linearity is based on the maximum deviation of the ratios R_g from the mean R_m of the *b* ratios of the measured voltage to the corresponding voltage of the comparison device. The maximum deviation is taken as a type B estimate of the standard uncertainty related to non-linearity of the scale factor in the extended voltage range (Figure 5):

$$u_{B1} = \frac{1}{\sqrt{3}} \cdot \max_{g=1}^{b} \left| \frac{R_g}{R_m} - 1 \right|$$



Key

F_1, F_2 scale factors determined by calibration with the reference divider in the calibration range

u_1, u_2 standard uncertainties of the scale factors F_1 and F_2

F mean of F_1 and F_2

R_1...R_b ratios determined in the extended voltage range for linearity test only

R_m mean of the ratios determined with a linear device in the extended voltage range

u_{B1} Type B standard uncertainty caused by non-linearity of the scale factor in the extended voltage range

Figure 5 – Linearity test of the measuring system with a linear device in the extended voltage range

5.3.2 Alternative methods in order of suitability

5.3.2.1 Comparison with an approved measuring system

The output of the measuring system shall be checked against the output of an approved measuring system according to the procedures described in 5.3.1. The linearity of the approved measuring system shall preferably have been established with the reference method during calibration given in 5.2.

5.3.2.2 Comparison with input voltage of a linear high voltage generator

The output of the measuring system shall be checked against the input voltage of the high voltage generator considering the voltage levels described in 5.3.1.

NOTE 1 The method is especially applicable for the charging voltage of multi-stage impulse generators or the alternating voltage input of a multi-stage direct voltage generator.

NOTE 2 Attention should be paid to the equal charging of all stages of a voltage generator. Sufficient time should be allowed for all stages to charge before triggering the generator.

5.3.2.3 Comparison with the output of an electric-field measuring instrument (field probe)

The measuring system can be checked against an electric-field responding measuring system which is so located in such a way that it measures a field proportional to the voltage being measured. The electric-field measuring system shall provide a response suitable for the type of voltage being measured.

NOTE 1 The method is expected to work up to the inception voltage for corona (see IEC 60270).

NOTE 2 This method is applicable to alternating voltage and to impulse voltages.

5.3.2.4 Comparison with a standard air gap according to IEC 60052

The measuring system for alternating or lightning/switching impulse voltage may be checked against a sphere gap. For a measuring system for direct voltage a rod/rod gap shall be applied. In both cases the comparison shall be made in accordance with the provisions of IEC 60052.

The complete linearity test shall be made within sufficiently short time that atmospheric conditions do not change and hence corrections need not be used. Otherwise corrections according to IEC 60060-1 shall be applied based on recorded atmospheric conditions.

5.3.2.5 Method for multi-section converting devices (voltage dividers)

For a converting device consisting of several identical high-voltage units the following tests shall be performed:

- a type test on an equivalent complete converting device (equipped with its electrodes) as specified in Clauses 6 to 9 shall be carried out;
- a measurement of the capacitance and/or resistance of each high-voltage unit at five equally spaced voltages (similar to that specified in 5.2.1.2) shall be effected. The scale factor shall be calculated for each voltage from the values of capacitance and/or resistance and that of the low-voltage arm;
- a check that the assembled converting device is not significantly affected by corona and other influences at the upper limit of the assigned measurement range.

NOTE Significant effects can be caused by visible and audible corona or leakage current.

5.4 Dynamic behaviour

5.4.1 General

The response of a component or a measuring system shall be determined in conditions representative of its use, particularly clearances to earthed and energized structures. The preferred methods of measurement are the amplitude/frequency response for direct or alternating voltages, and determination of the scale factors and time parameters at the upper and lower limit of the nominal epoch for impulse voltages (5.4.3). Additional information on unit step-response measurements is given in Annex C.

A type B estimate of the relative standard uncertainty related to the dynamic behaviour is given by:

$$u_{B2} = \frac{1}{\sqrt{3}} \max_{i=1}^{k} \left| \frac{F_i}{F} - 1 \right|,$$

where k is the number of scale factor determinations within a frequency range, or within a range of impulse time parameters defining the nominal epoch, F_i are the individual scale factors and F is the mean scale factor within the nominal epoch.

5.4.2 Determination of the amplitude/frequency response

The system or component is subjected to a sinusoidal input of known amplitude, usually at low level, and the output is measured. This measurement is repeated for an appropriate range of frequencies. The deviations of the scale factor are evaluated according to the above formula (5.4.1).

5.4.3 Reference method for impulse voltage measuring systems

Records of the impulse voltage taken for calibration of the scale factor described in (5.2) are used for the limits of the nominal epoch, and the uncertainty contribution of voltage and time-parameter measurements shall be evaluated according to the above formula (5.4.1).

NOTE For additional information by unit step response measurement and evaluation see Annex C.

5.5 Short-term stability

The maximum voltage of the assigned measurement range shall be applied to the measuring system continuously (or at the assigned rate for impulses) for a period appropriate to the anticipated use. The scale factor shall be measured as soon as the maximum voltage has been reached and again immediately before the voltage is reduced.

NOTE 1 The short term stability test is intended to cover the effects of self-heating on the converting device.

NOTE 2 The period of voltage application should not be longer than the assigned operating time, but can be limited to a time sufficient to reach equilibrium.

The result of the test is an estimate of the change of scale factor within the voltage application time from which the standard uncertainty contribution is obtained as a type B estimate:

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

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

5.6 Long-term stability

The stability of the scale factor shall be considered and evaluated over a long time-span and is usually estimated as an uncertainty contribution valid for a projected time of use (usually until the next calibration), T_{use}. The evaluation can be based on manufacturer's data or on results of a series of performance tests. The result of the evaluation is an estimate of a change of the scale factor. The evaluation delivers a standard uncertainty contribution, which is a type B estimate:

$$u_{B4} = \frac{1}{\sqrt{3}} \cdot \left| \frac{F_2}{F_1} - 1 \right| \cdot \frac{T_{use}}{T_2 - T_1} ,$$

where F_1 and F_2 are the scale factors of two consecutive performance tests made at times T_1 and T_2.

In cases where a number of performance test results are available, the long-term stability can be characterised by the type A contribution:

$$u_{B4} = \frac{T_{use}}{T_{mean}} \sqrt{\frac{\sum_{i=1}^{n} \left(\frac{F_i}{F_m} - 1 \right)^2}{n-1}} ,$$

where the results of repeated performance tests are the scale factors F_{i}, with a mean value F_{m} and repeated with a mean time interval T_{mean}.

NOTE Long-term stability is usually stated for a period of one year.

5.7 Ambient temperature effect

The scale factor of a measuring system can be affected by ambient temperature. This can be quantified by determination of the scale factor at different ambient temperatures or by computations based on properties of components. Details of test or calculations shall be included in the record of performance.

The result of a test or calculation is an estimate of a change of the scale factor due to ambient temperature. The related standard uncertainty is the following type B estimate:

$$u_{B5} = \frac{1}{\sqrt{3}} \cdot \left| \frac{F_T}{F} - 1 \right| ,$$

where F_T is the scale factor at the considered temperature and F is that at the calibration temperature.

NOTE 1 If the deviation F_T from F is greater than 1 %, a correction of the scale factor is recommended.

NOTE 2 Self-heating effect is covered by the short-term stability test.

NOTE 3 A temperature correction factor for the scale factor may be used in cases where the ambient temperature varies over a wide range. Any temperature corrections to be used should be listed in the record of performance. For cases where temperature correction has been applied, the uncertainty u_{B5} of the temperature correction factor may be taken as the uncertainty contribution.

5.8 Proximity effect

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

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

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

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

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

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

5.9 Software effect

The way that the software handles evaluation of measured data may introduce an uncertainty that shall be estimated. This can be done by evaluation of a set of test data with established reference values. For impulse voltages see IEC 61083-2.

The result of the evaluation is an estimate of the influence of data processing, from which the relative standard uncertainty contribution u_{B7} is obtained as a type B estimate.

5.10 Uncertainty calculation of the scale factor

5.10.1 General

A simplified procedure to determine the expanded uncertainty of the assigned scale factor F of a measuring system is given here. It is based on several assumptions, which in many cases may be true, but should be verified in each individual case. The main assumptions are as follows:

a) There is no correlation between the measurement quantities;
b) Standard uncertainties evaluated by the method of Type B are assumed to have a rectangular distribution.
c) The largest three uncertainty contributions to uncertainty have approximately equal magnitude.

These assumptions lead to a procedure of evaluation of the expanded uncertainty of the scale factor *F*, both for the calibration situation and for the use of an approved measuring system in measurements.

The expanded uncertainty of calibration U_{cal} is estimated from the uncertainty of the calibration of the reference system and from influence of other quantities explained in this subclause, such as the stability of the reference measuring system and ambient parameters during the calibration.

The expanded uncertainty of a measurement U_{M} of the test quantity is evaluated from the uncertainty of the calibration of the scale factor of the approved measuring system and from the influence of other quantities discussed in 5.10.3, such as the stability of the measuring system and ambient parameters during the measurement as they are not considered in the calibration certificate.

Further methods for estimating uncertainty are given in the ISO/IEC Guide 98-3 and are also described in Annex A and Annex B.

5.10.2 Uncertainty of the calibration

The relative expanded uncertainty of a calibration of the scale factor U_{cal} is calculated from the uncertainty of the reference measuring system and the Type A and Type B uncertainties explained in this subclause:

$$U_{\mathrm{cal}} = k \cdot u_{\mathrm{cal}} = 2\sqrt{u_{\mathrm{ref}}^2 + u_{\mathrm{A}}^2 + \sum_{i=0}^{N} u_{\mathrm{B}i}^2} ,$$

where:

k = 2 is the coverage factor for a coverage probability of approximately 95 % and normal distribution;

u_{ref} is the combined standard uncertainty of the scale factor of the reference measuring system at its calibration;

u_{A} is the statistical Type-A uncertainty in the determination of the scale factor.

u_{B0} is the non-linearity contribution to standard uncertainty determined during calibration of the scale factor (see 5.2);

u_{Bi} are the contributions to the combined standard uncertainty of the scale factor caused by the i^{th} influence quantity and evaluated as a Type B contribution (Annex A). These contributions are related to the reference measuring system, and arise from non-linearity, short- and long-term instabilities, etc. and are determined either by additional measurements or estimated from other data sources according to 5.3 to 5.9. Influences related to the approved measuring systems, such as its short-term stability, and resolution of the measurement shall also be taken into account if they are significant during the calibration.

NOTE If the calibration is performed over the full assigned measurement range (5.2.1.2), no separate linearity test (5.3) is required.

In cases where the assumptions mentioned above are not valid, the procedures given in Annex A or, if necessary, in the ISO/IEC Guide 98-3:2008 shall be applied.

The number *N* of Type B uncertainty contributions may differ for the different types of test voltages (Clauses 6 to 9). More information on the Type B contributions is given in the relevant clauses.

If the assigned scale factor of the measuring system is calculated from those of its components (5.2.2), the standard uncertainties of the calibration of the components shall be combined with those describing additional conditions of the measuring system and its environment (see Annex A).

5.10.3 Uncertainty of measurement using an approved measuring system

Estimation of the expanded uncertainty of measurement of the test voltage value is the responsibility of the user. However, this estimation may be given for a defined range of measurement conditions in conjunction with the calibration certificate.

The relative expanded uncertainty of measurement of the test voltage value U_{M} is calculated from the combined standard uncertainty of the assigned scale factor as determined in the calibration of the approved measuring system and additional Type B uncertainty contributions explained in this subclause:

$$U_M = k \cdot u_{\mathrm{M}} = 2\sqrt{u_{\mathrm{cal}}^2 + \sum_{i=0}^{N} u_{\mathrm{B}i}^2},$$

where:

- $k = 2$ is the coverage factor for a coverage probability of approximately 95 % and normal distribution;
- u_{M} is the combined standard uncertainty of the measurement using the approved measuring system, valid for a projected time of use, e.g. a calibration interval;
- u_{cal} is the combined standard uncertainty of the scale factor of the approved measuring system determined at the calibration (see 5.10.2);
- $u_{\mathrm{B}i}$ is the contribution to the combined standard uncertainty of the scale factor of the approved measuring system and caused by the i^{th} influence quantity, evaluated as a Type B contribution. These contributions are related to normal use of the approved measuring system, and arise from non-linearity, short- and long-term instabilities, etc. and are determined according to 5.3 to 5.9 based either on additional measurements or estimated from other data sources. Other significant influences shall also be taken into account, e.g. resolution of instrument display of the approved measuring system.

NOTE The calibration certificate may include information on both the uncertainty of the calibration, U_{cal}, and the relative expanded uncertainty of measurement of the test voltage value, U_{M}, when using the approved measuring system under stated, predefined conditions.

In cases where the assumptions mentioned above in 5.10.1 are not valid, the procedures given in Annex A or, if necessary in the ISO/IEC Guide 98-3, shall be applied.

The number *N* of Type B uncertainty contributions may differ for the different types of test quantities (Clauses 6 to 9, voltages and time parameters).

5.11 Uncertainty calculation of time parameter measurement (impulse voltages only)

5.11.1 General

An approved measuring system for impulse voltages shall be able to measure the time parameters (T_1, T_2, T_p, T_c) within the specified uncertainty limits when the parameter lies within its specified range. For front time this is usually the nominal epoch. The experimental proof can be given either by the comparison method or by the component method. The proof may also be given by calculation, using the convolution method on the basis of the experimental step response (Annex C and D).

The general procedure for evaluating the time parameters and their uncertainties is described for the front time T_1, determined by the comparison method (see example in Clause B.3). It is applicable for other time parameters in the same way.

NOTE It should be remembered that the estimation of the uncertainty of time parameters results in an absolute uncertainty value

5.11.2 Uncertainty of the time parameter calibration

The front times T_1 of n impulse voltages shall be evaluated simultaneously with the measuring system under test, denoted by X, and the reference system, denoted by N. The error of the reference measuring system is assumed to be negligible. The mean error of the front times is

$$\Delta T_1 = \frac{1}{n}\sum_{i=1}^{n}\left(T_{1\mathrm{X,i}} - T_{1\mathrm{N,i}}\right)$$

and the experimental standard deviation is

$$s(\Delta T_1) = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(\Delta T_{1,\mathrm{i}} - \Delta T_1\right)^2}$$

where $\Delta T_{1,\mathrm{i}}$ is the i^{th} difference of the front times measured by the systems X and N.

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

NOTE 2 In general, the front times are evaluated from the same records of N and X, used to evaluate the peak values for determining the scale factor (5.2.2.1).

From $s(\Delta T_1)$, the Type A standard uncertainty is calculated:

$$u_\mathrm{A} = \frac{s(\Delta T_1)}{\sqrt{n}}.$$

The comparison is performed at a suitable voltage level using at least two front times, including the minimum and maximum T_1 values of the nominal epoch, for which the measuring system is to be approved. An additional T_1 value in the middle of the nominal epoch can be added. The standard uncertainty Type A of the time parameter measurement is obtained as the largest of the single standard uncertainties determined for the different T_1 values. For each of the different T_1 values, the mean error $\Delta T_{1,\mathrm{j}}$ is calculated as described above. The overall mean of the $m \geq 2$ mean errors is:

$$\Delta T_{1\mathrm{m}} = \frac{1}{m}\sum_{j=1}^{m}\Delta T_{1,\mathrm{j}}\ .$$

The maximum difference between the individual values $\Delta T_{1,j}$ and their mean value ΔT_{1m} is taken to determine the Type B uncertainty u_B by:

$$u_B = \frac{1}{\sqrt{3}} \max_{j=1}^{m} \left| \Delta T_{1,j} - \Delta T_{1m} \right| .$$

NOTE More generally, the reference measuring system N may be characterised in the same manner by its mean error of the front time, denoted by ΔT_{1ref}, as stated in its calibration certificate for the nominal epoch. The resultant error of the calibrated system X itself for front time measurements is

$$\Delta T_{1cal} = \Delta T_{1m} + \Delta T_{1ref} .$$

The expanded uncertainty of the time parameter calibration, equal to that of the resultant mean error, ΔT_{1cal}, is determined by:

$$U_{cal} = k \cdot u_{cal} = 2\sqrt{u_{ref}^2 + u_A^2 + u_B^2} ,$$

where:

u_{cal} is the combined standard uncertainty of the mean front time error, ΔT_{1cal}, of the calibrated measuring system;

$k = 2$ is the coverage factor for a coverage probability of approximately 95 % and normal distribution;

u_{ref} is the combined standard uncertainty of the mean front time error, ΔT_{1ref}, of the reference measuring system;

u_A is the type A standard uncertainty of the mean front time error, ΔT_{1m}, of the calibrated measuring system;

u_B is the type B standard uncertainty of the mean front time error ΔT_{1m} of the calibrated measuring system.

Additional contributions to the expanded uncertainty U_{cal} may be important in special cases and shall be considered.

5.11.3 Uncertainty of time parameter measurement using an approved measuring system

Estimation of the expanded uncertainty of a time parameter measurement is the responsibility of the user. However, this estimation may be given for defined range of measuring conditions in conjunction with the calibration certificate.

NOTE If the expanded uncertainty of the time parameter calibration is less than 70 % of the expanded uncertainty specified for time parameter measurement in this standard, it can in general be assumed that the uncertainty of using the approved measuring system for time parameter measurement U_M is equal to U_{cal}.

The expanded uncertainty of the time parameter measurement U_M shall be calculated according to

$$U_M = k \cdot u_M = 2\sqrt{u_{cal}^2 + \sum_{i=1}^{N} u_{Bi}^2} ,$$

where:

u_{cal} is the combined standard uncertainty of the mean front time error, ΔT_{1cal}, of the calibrated measuring system;

$k = 2$ is the coverage factor for a coverage probability of approximately 95 % and normal distribution;

u_{Bi} is the contribution to the combined standard uncertainty of the time parameter of an impulse using the approved measuring system and caused by the i^{th} influence quantity and evaluated as a Type B contribution. These contributions are related to normal use of the approved measuring system, and arise for example from long-term instabilities, software influence, etc., but also from the influence of having non-perfect impulse shapes. They are determined according to 5.3 to 5.9, based either on additional measurements or estimated from other data sources. In some situations further influences shall also be taken into account, e.g. resolution of instrument displays.

u_M is the combined standard uncertainty of the time parameter of an impulse voltage measured with the approved measuring system, valid for an projected period of use;

Additional contributions to the expanded uncertainty may be important in special cases and shall be considered when calculating U_M, e.g. when the impulse voltage is superimposed by front oscillations.

NOTE When the approved measuring system is used to measure impulse voltages without oscillations, the measured time parameter T_{1meas} can be corrected by the resultant error ΔT_{1cal} of the relevant time parameter determined in the calibration:

$$T_{1corr} = T_{1meas} - \Delta T_{1cal}.$$

The same procedures can be applied to other time parameters. The expanded uncertainty of a corrected time parameter, T_{1corr}, should be given according to Annex B, Example B.3.

5.12 Interference test (transmission system and instrument for impulse voltage measurements)

The test shall be made on the measuring system, with its cable or transmission system disconnected, located in its usual position and short-circuited at its input terminals without changing the earth connections of the cable or transmission system. An interfering condition shall be produced at the input of the measuring system by a disruptive discharge with an impulse voltage representative of voltage, shape and instant of a possible discharge to be applied during the HV tests, and the instrument shall record the output.

NOTE To protect the converting device (voltage divider) output from over-voltages, it may be advisable to short-circuit the divider output terminal.

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

To pass the interference test, the maximum amplitude of the measured interference should be less than 1 % of the output of the measuring system when measuring the test voltage. Interference greater than 1 % is permitted provided it is shown that it does not affect the measurement.

5.13 Withstand tests of converting device

A converting device shall pass a dry withstand test performed with a voltage of the required frequency or shape at a specified voltage.

NOTE 1 The recommended withstand test level is 110 % of the rated operating voltage. For the procedures of withstand tests see IEC 60060-1.

The withstand tests shall be performed at the polarity (or polarities) for which the system is intended.

Wet tests and pollution tests, when specified, are performed as type tests.

NOTE 2 Design and construction of any component of an approved measuring system should be such that it can withstand a disruptive discharge at the test object without any change in its characteristics.

6 Measurement of direct voltage

6.1 Requirements for an approved measuring system

6.1.1 General

The general requirement is to measure the test voltage value according to IEC 60060-1 (arithmetic mean value) with an expanded uncertainty $U_M \leq 3$ %.

The uncertainty limits shall not be exceeded in the presence of ripple, the magnitude of which is within the limits given in IEC 60060-1.

NOTE Attention is drawn to the possible presence of alternating voltages coupled to the measuring system and affecting the reading of the measuring instrument.

6.1.2 Uncertainty contributions

For a direct voltage measuring system, the expanded uncertainty of measurement U_M shall be evaluated with a coverage probability of 95 %, according to 5.10.3 and – if necessary - Annexes A and B. Tests for assessing contributions to uncertainty which are usually considered are summarized in Table 1. Other contributions can be important in some cases and so shall be considered in addition.

6.1.3 Requirement on converting device

A converting device for direct voltage, usually a resistive voltage divider or a voltage measuring impedance (high-voltage resistor), shall be constructed so as to ensure that leakage current on its external insulating surfaces has a negligible influence on the measuring uncertainty.

NOTE To ensure that the influence of leakage current is negligible, a measuring current as high as 0,5 mA at the rated voltage may be necessary.

6.1.4 Dynamic behaviour for measuring voltage changes

The time constant of the high-voltage measuring system shall not be greater than 0,25 s for the measurement of direct voltages that rise or fall with rates in the order of 1 % of the test voltage value per second.

NOTE In general, the instruments used for the measurement of the test voltage value (i.e. the arithmetic mean), are not affected by the ripple present. However, if instruments with fast response are used, it may become necessary to ensure that the measurement is not adversely affected by the ripple.

When the transient voltage drop during pollution testing is measured, the time constant of the measuring system shall be less than one third of the rise time of the transient.

6.2 Tests on an approved measuring system

The tests according to Clause 5, summarized in Table 1, are necessary for the qualification of measuring systems and their components as well as for the estimation of the expanded uncertainty of measurement, for exceptions see 4.4.2.

The results of the type and routine tests can be taken from manufacturer's data. Routine tests shall be performed on each component.

Table 1 – Tests required for an approved direct voltage measuring system

Type of test	Type test	Routine test	Performance test	Performance check
Scale factor at calibration			5.2	
Scale factor check				6.3
Linearity, see NOTE 2		5.3	5.3 (if applicable)	
Dynamic behaviour	5.4			
Short-term stability		5.5		
Long-term stability	5.6		5.6 (if applicable)	
Ambient temperature effect	5.7			
Proximity effect, see NOTE 3	5.8 (if applicable)		5.8 (if applicable)	
Software effect	5.9 (if applicable)			
Dry withstand test on converting device	5.13	5.13 (if applicable)		
Wet or polluted withstand test on converting device	5.13 (if applicable)			
Scale factor of converting device	5.2.2	5.2.2		
Scale factor of transmission system other than a cable	5.2.2	5.2.2		
Scale factor of measuring instrument	5.2.2	5.2.2		
Responsibility	on components, by manufacturer		on the system by user, see NOTE 1	
Recommended repetition rate	only once (type and routine test)		proposed annually, but at least every 5 years	according to stability, but at least annually

NOTE 1 The above listed tests should also be applied to single components if performance tests are made according to the alternative method (see 5.2.2). To obtain the uncertainty of measurement of the approved measuring system those of the components should be combined as demonstrated in Annex B.

NOTE 2 A linearity test according to 5.3 is only required if the calibration cannot be performed by comparison over the full assigned measurement range (5.2.1.2).

NOTE 3 Proximity effects can be caused by corona and related space charge effects. Investigation of the proximity effect in the performance test is only necessary if the type test data are not sufficient.

6.3 Performance check

6.3.1 General

The scale factor(s) of an approved measuring system can be checked by one of the following methods.

6.3.2 Comparison with an approved measuring system

A comparison shall be made with another approved measuring system using the procedure of 5.2 or with a rod-rod gap according to IEC 60052. If the difference between the two measured values is within ± 3 %, the assigned scale factor is taken as valid. If the difference is larger, then a new value of the assigned scale factor shall be determined in a performance test (calibration) as described in 5.2.

6.3.3 Check of the scale factors of the components

The scale factor(s) of each component shall be checked, using an internal or an external calibrator having an expanded uncertainty of no more than 1 %. If the difference of the scale factor of each component from its previous value is not larger than ±1 %, the assigned scale factor is taken as still valid. If any difference exceeds 1 %, then a new value of the assigned scale factor shall be determined in a performance test (calibration) as described in 5.2.

6.4 Measurement of ripple amplitude

6.4.1 Requirements

The ripple amplitude shall be measured with an expanded uncertainty of no more than 10 % of the ripple amplitude or 1 % of the arithmetic mean value of the direct voltage, whichever is larger.

Separate ripple measuring systems may be used to measure the mean value of the voltage and the ripple amplitude, or the same converting device may be used with two separate instruments.

The upper –15 % limit frequency of the amplitude/frequency response of the ripple measuring system shall be greater than 5 times, and the lower –15 % limit frequency less than 0,5 times that of the fundamental frequency f of the ripple.

NOTE The requirement on the lower limit frequency can be verified at the frequency of its supply voltage in many cases.

6.4.2 Uncertainty contributions

For a ripple voltage measuring system the uncertainty shall be estimated according to Annex A and in addition uncertainty contributions mentioned in 5.3 to 5.9 shall be considered. For details see also the related clauses for measurement of alternating voltages (Clause 7). Other contributions can be important in individual cases and the information given here is for guidance only.

6.4.3 Calibrations and tests on an approved ripple voltage measuring system

The tests specified in Table 2 shall be applied only to systems used to measure the ripple amplitude.

The compliance with type test requirements can be proved by tests on a device of the same design or sometimes be derived from manufacturer's data. Routine tests shall be performed on each component. See 4.4.2 for exceptions.

Other uncertainty contributions can be important in individual cases and the information given here is for guidance only.

6.4.4 Measurement of the scale factor at the ripple frequency

The scale factor of the ripple measuring system shall be determined at the fundamental frequency f of the ripple, with an expanded uncertainty of no more than 3 %. This scale factor may also be determined as the product of the scale factors of the components.

6.4.5 Dynamic behaviour by amplitude/frequency response

The measuring system is subjected to a sinusoidal input of known amplitude, usually at low level, and the output is measured. This measurement is repeated for a range of frequencies approximately between 0,5 times and 7 times the fundamental frequency of the ripple. The difference of the measured voltages shall be within 3 dB.

6.4.6 Performance check for ripple measuring system

The scale factor of an approved measuring system can be checked by one of the methods described for alternating voltage measuring systems in 7.4.

Table 2 – Required tests for uncertainty contributions in ripple measurement

Type of test	Type test	Routine test	Performance test	Performance check
Scale factor of measuring system at the calibration			5.2	
Scale factor check				6.4.6/7.4
Dynamic behaviour for ripple		6.4.5	6.4.5	
Long-term stability	5.6			
Ambient temperature effect	5.7			
Responsibility	on components, by manufacturer		on the system by user	
Recommended repetition rate	only once (type and routine test)		proposed annually, but at least every 5 years	according to stability, but at least annually

7 Measurement of alternating voltage

7.1 Requirements for an approved measuring system

7.1.1 General

The general requirement is to measure the test voltage value according to IEC 60060-1 (peak/ $\sqrt{2}$ or r.m.s. value) at its rated frequency with an expanded uncertainty $U_M \leq 3$ %.

7.1.2 Uncertainty contributions

For an alternating voltage measuring system the expanded uncertainty U_M shall be evaluated with a coverage probability of 95 % according to 5.10.3 and - if necessary - Annexes A and B. Tests for assessing contributions to uncertainty which are usually considered are summarized in Table 3. Other contributions can be important in some cases and so shall be considered in addition.

7.1.3 Dynamic behaviour

The amplitude-frequency response of a measuring system, intended for operation at one single fundamental frequency f_{nom}, shall be within the marked area of Figure 6, derived from the uncertainty requirements. Number pairs in the diagram show the normalised frequency (logarithmic scale) and the corresponding deviation at the corner points of the limit lines. Performance shall be proven from f_{nom} to 7 f_{nom} by tests or circuit analysis. The amplitude-frequency response outside this range is given for information only.

A measuring system can also be approved for a range of fundamental frequencies (e.g. 45 Hz to 65 Hz according to IEC 60060-1). The scale factor shall in such cases be constant within 1 % from the lowest fundamental frequency f_{nom1} up to the highest fundamental frequency f_{nom2}. The amplitude-frequency response inside the interval f_{nom1} to 7 f_{nom2}, shall be within the marked area of Figure 7. Number pairs in the diagram show the normalised frequency and the corresponding permitted deviation from the ideal response at the corner points of the limit lines. Performance shall be proven from f_{nom1} to 7 f_{nom2} by tests or circuit analysis. The amplitude-frequency response outside this range is given for information only.

Special requirements on dynamic behaviour may be specified by the relevant technical committee.

NOTE 1 Measuring systems complying with these requirements are considered to have a frequency response suitable for measurement of the total harmonic distortion (THD) on the test voltage.

NOTE 2 The frequency response outside the marked area, although not required, represents good practice.

NOTE 3 Amplitude-frequency response measurements can be waived for measuring systems used on alternating voltage sources (e.g. series resonant systems) if it can be demonstrated that the peak-to-r.m.s. ratio of the test voltage equals $\sqrt{2}$ within $\pm$ 1 % for all expected operation conditions.

NOTE 4 In certain cases, it may be necessary to measure transient voltages superimposed on an alternating voltage. No requirements for this are given here, but some guidance may be obtained from Clause 8.

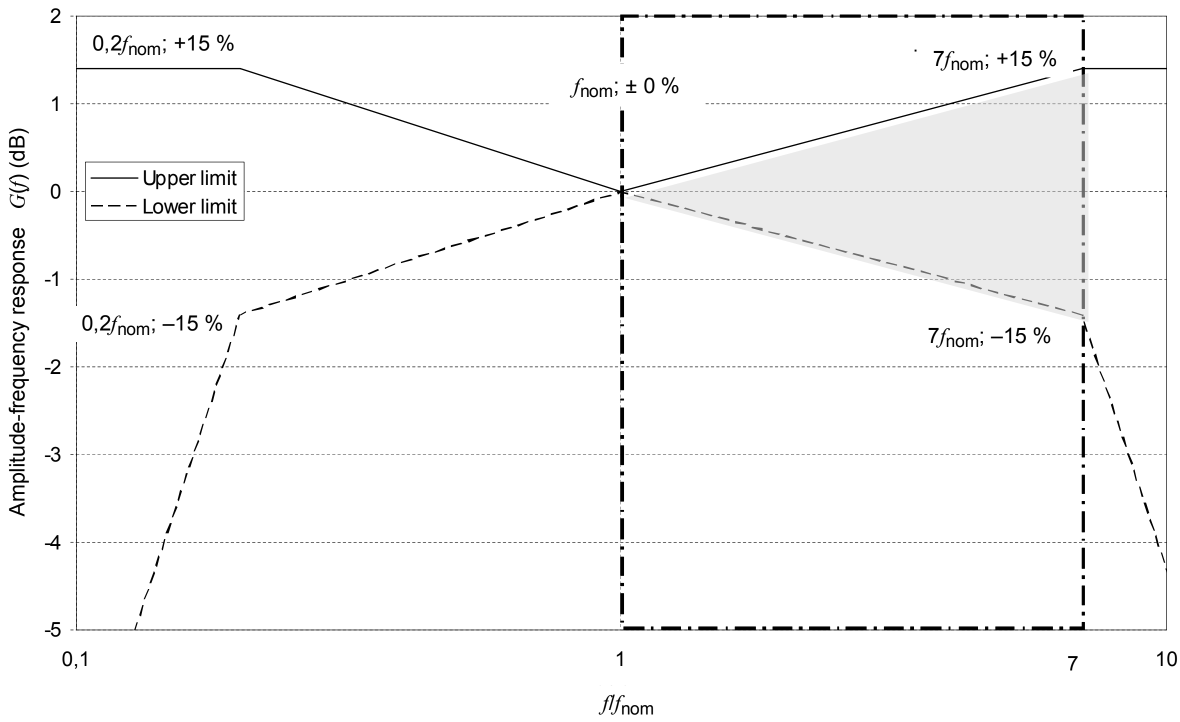


Figure 6 – Shaded area for acceptable normalised amplitude-frequency responses of measuring systems intended for single fundamental frequencies f_{nom} *(to be* tested in the range (1....7) f_{nom})

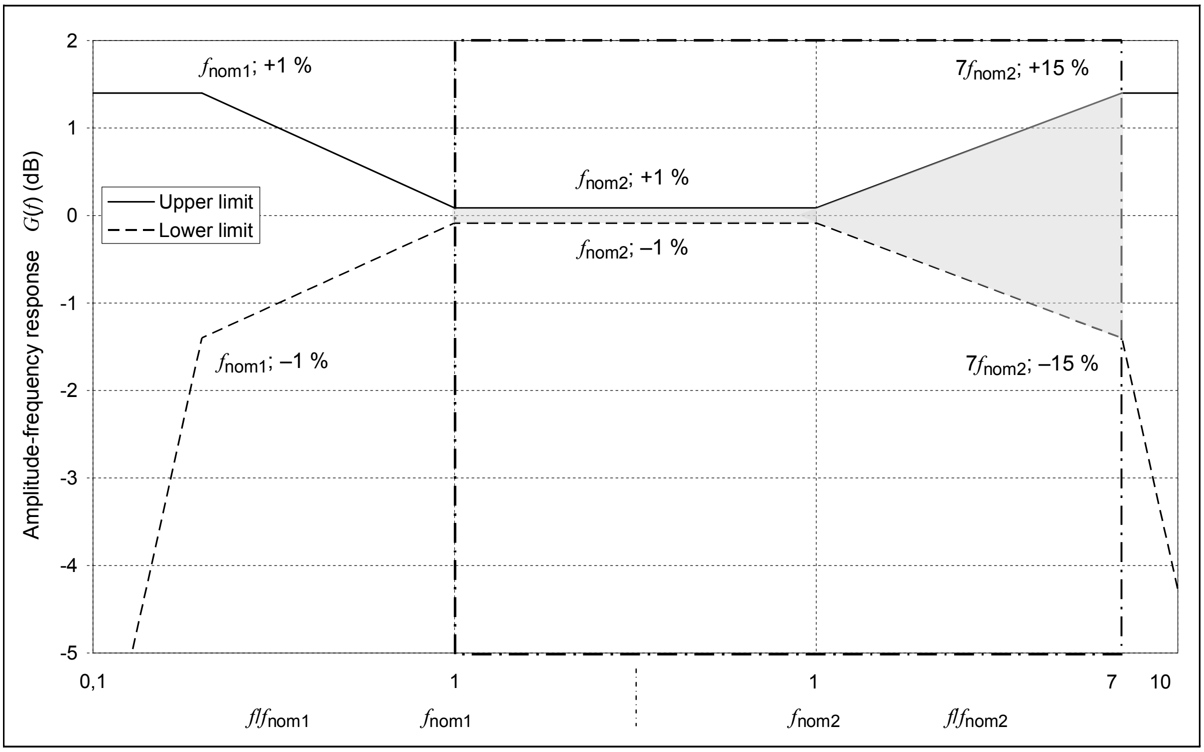


Figure 7 – Shaded area for acceptable normalised amplitude-frequency responses of measuring systems intended for a range of fundamental frequencies f_{nom1} to f_{nom2} (to be tested in the range f_{nom1} to 7 f_{nom2})

7.2 Tests on an approved measuring system

The tests according to Clause 5, summarized in Table 3, are necessary for the qualification of an alternating voltage measuring system and its components as well as for the estimation of the expanded uncertainty of measurement. For exceptions see 4.4.2.

The results of the type and routine tests can be taken from manufacturer's data. Routine tests shall be performed on each unit.

7.3 Dynamic behaviour test

To determine the dynamic behaviour, the system is subjected to a sinusoidal input of known amplitude, usually at low level, and the output is measured. This measurement is repeated for the range of frequencies between 1 time and 7 times the test frequency. The result shall be in accordance with clause 7.1.3.

7.4 Performance check

7.4.1 General

The scale factor(s) of an approved measuring system can be checked by one of the following methods.

7.4.2 Comparison with an approved measuring system

A comparison shall be made with another approved measuring system using the procedure of 5.2 or with a sphere gap according to IEC 60052. If the difference between the two measured values is within ±3 %, the assigned scale factor is taken as still valid. If the difference is larger, then a new value of the assigned scale factor shall be determined in a performance test (calibration) (see 5.2).

7.4.3 Check of the scale factors of the components

The scale factor(s) of each component can be checked using an internal or an external calibrator having an expanded uncertainty of no more than 1 %. If the difference of each scale factor from its previous value is not more than ±1 %, the assigned scale factor is taken as still valid. If any difference exceeds 1 % then a new value of the assigned scale factor shall be determined (see 5.2).

Table 3 – Tests required for an approved alternating voltage measuring system

Type of test	Type test	Routine test	Performance test	Performance check
Scale factor at the calibration			5.2	
Scale factor check				7.4
Linearity, see NOTE 2		5.3	5.3 (if applicable)	
Dynamic behaviour	5.4/7.3		5.4	
Short-term stability		5.5		
Long-term stability	5.6		5.6 (if applicable)	
Ambient temperature effect	5.7			
Proximity effect, see NOTE 3	5.8 (if applicable)		5.8 (if applicable)	
Software effect	5.9 (if applicable)			
Dry withstand test on converting device	5.13	5.13 (if applicable)		
Wet or polluted withstand test on converting device	5.13 (if applicable)			
Scale factor of converting device	5.2.2	5.2.2		
Scale factor of transmission system other than a cable	5.2.2	5.2.2		
Scale factor of measuring instrument	5.2.2	5.2.2		
Responsibility	on components, by manufacturer		on the system, by user, see NOTE 1	
Recommended repetition rate	only once (type and routine test)		proposed annually but at least every 5 years	according to stability but at least annually

NOTE 1 The above listed tests should also be applied to the single components if performance tests are made according to the alternative method (see 5.2.2). To obtain the uncertainty of measurement of the approved measuring system, those of the components must be combined as demonstrated in Annex B.

NOTE 2 A linearity test according to 5.3 is only required if the calibration cannot be performed by comparison over the full measurement range (5.2.1.2).

NOTE 3 Investigation of the proximity effect in the performance test is only necessary if the type test data are not sufficient.

8 Measurement of lightning impulse voltage

8.1 Requirements for an approved measuring system

8.1.1 General

The general requirements are:

- to measure the test voltage value according to IEC 60060-1 for full and tail-chopped impulses with an expanded uncertainty $U_{M1} \leq 3$ %;
- to measure the peak value of front chopped impulses with an expanded uncertainty $U_{M2} \leq 5$ % (0,5 $\mu s < T_c <$ 2 μs);
- to measure the time parameters which define the waveform according to IEC 60060-1 with an expanded uncertainty $U_{M3} \leq 10$ %;
- to measure oscillations which may be superimposed on an impulse to ensure that they do not exceed the permitted levels given in IEC 60060-1.

NOTE No recommendations are given for the measurement of voltage collapse since no IEC apparatus committee has yet specified a requirement.

8.1.2 Uncertainty contributions

For a lightning impulse voltage measuring system, the expanded uncertainty of measurement U_M shall be evaluated with a coverage probability of 95 %; according to 5.10.3, 5.11.3 and – if necessary - Annexes A and B. Tests for assessing contributions to uncertainty which are usually considered are summarized in Table 4. Other contributions can be important in some cases and so shall be considered in addition.

8.1.3 Requirement on measuring instrument

The measuring instrument shall comply with IEC 61083-1 and IEC 61083-2.

8.1.4 Dynamic behaviour

The dynamic behaviour of a measuring system is adequate for the measurement of peak voltage and time parameters over the nominal epoch for waveforms specified in the record of performance when:

- the scale factor is constant within the following limits:
  - within ± 1 % for full and tail-chopped impulses
  - within ± 3 % for front-chopped impulses
- the expanded uncertainty of the time parameters measurement is not greater than 10 %.

NOTE 1 In order to reproduce, in the recorded curve, oscillations that may be superimposed on an impulse, the relevant upper limit frequency may be several MHz.. A measuring system with a response parameter T_α equal or less than several tens of nanoseconds can be considered suitable (see Annex C). These limits are under consideration.

NOTE 2 Preferably one measuring system is used to measure all of the required quantities, i.e. the peak value, the time parameters, and oscillations. However, many systems which could be approved for measurements of peak value and time parameters cannot be approved for measurements of oscillations. In this case a measuring system may be approved for measurements of peak voltage and time parameters while an auxiliary system is approved for measurements of oscillations.

8.1.5 Connection to the test object

The converting device shall be connected directly to the terminals of the test object. The converting device shall not be connected between the voltage source and the test object. The lead to the converting device shall carry only the current to the measuring system. The converting device should be placed so that coupling between the test and measuring circuits is negligible.

NOTE Exceptions are possible, e.g. for testing with combined voltages (see IEC 60060-1).

8.2 Tests on an approved measuring system

The tests according to Clause 5, summarized in Table 4, are necessary for the qualification of a lightning impulse voltage measuring system and its components as well as for the estimation of the expanded uncertainty. For exceptions see 4.4.2.

The results of the type and routine tests can be taken from manufacturer's data. Routine tests shall be performed on each unit.

Table 4 – Tests required for an approved lightning impulse voltage measuring system

Type of test	Type test	Routine test	Performance test	Performance check
Scale factor/time parameter at the calibration			5.2 5.11/8.3	
Scale factor check				8.5
Linearity, see NOTE 2		5.3	5.3 (if applicable)	
Dynamic behaviour	5.4/8.4		5.4/8.4	8.5
Long-term stability	5.6		5.6 (if applicable)	
Ambient temperature effect	5.7			
Proximity effect, see NOTE 3	5.8 (if applicable)		5.8 (if applicable)	
Software effect (IEC 61083-2)	5.9 (if applicable)			
Interference test			5.12	5.12
Dry withstand test	5.13	5.13 (if applicable)		
Wet or polluted withstand test	5.13 (if applicable)			
Scale factor/time parameters of converting device	5.2.2	5.2.2		
Scale factor/time parameters of transmission system other than a cable	5.2.2	5.2.2		
Scale factor/time parameters of measuring instrument	5.2.2 IEC 61083	5.2.2 IEC 61083		
Responsibility	on components, by manufacturer		on the system, by user, see NOTE 1	
Recommended repetition rate:	only once (type and routine test)		Proposed annually, but at least every 5 years	according to stability, but at least annually

NOTE 1 The above listed tests should also be applied to the single components if performance tests are made according to the alternative method (see 5.2.2). To obtain the uncertainty of measurement of the approved measuring system, those of the components should be combined as demonstrated in Annex B.

NOTE 2 A linearity test according to 5.3 is only required if the calibration cannot be performed by comparison over the full measurement range (5.2.1.2).

NOTE 3 Investigation of the proximity effect in the performance test is only necessary if the type test data are not sufficient.

8.3 Performance test on measuring systems

8.3.1 Reference method (preferred)

The assigned scale factor and the dynamic behaviour of the measuring system shall be determined by comparison with a reference measuring system, using the procedure given in 5.2. It is recommended to apply a substitute test object between the two measuring systems.

The performance over the nominal epoch t_{min} to t_{max} shall be proven by using impulses with two different waveforms such that:

For full and tail-chopped impulses:

- t_{min} is equal to the shortest front time T_{1min}
- t_{max} is equal to the longest front time T_{1max}
- both these waveforms should approximately have the longest time to half-value T_{2max} for which the measuring system is to be approved.

For front-chopped impulses:

- t_{min} is equal to the shortest time to chopping T_{cmin}
- t_{max} is equal to the longest time to chopping T_{cmax}

8.3.2 Alternative method supplemented by a measurement of the step response according to Annex C

The assigned scale factor is determined by a comparative measurement against a reference measuring system according to 5.2 using full impulses with one front time T_{1cal} within the range T_{1min} to T_{1max} and a time to half-value approximately equal to the longest time to half-value T_{2max} for which the measuring system is to be approved. Alternatively it can be determined from the scale factors of the components (5.2.2).

For measuring systems intended to measure front-chopped impulses, the calibration impulses should be of a time to chopping T_{ccal} within the range T_{cmin} to T_{cmax}.

In addition the step response of the measuring system shall be measured according to Annex C. The reference level within the reference level epoch(s) for which the system is to be approved shall not differ from the value of the step response at the time:

- T_{1cal} by more than ±1 % for full and tail-chopped impulses, and also
- T_{ccal} by more than ±1 % for front-chopped impulses.

The step response shall not deviate by more than 2 % from the reference level in the reference level epoch $0{,}5T_{1min}$ to $2T_{1max}$ (Annex C). The step response shall further not deviate by more than 5 % in the range $2T_{1max}$ to $2T_{2max}$ where T_{2max} is the longest time to half-value for which the system is to be approved.

8.4 Dynamic behaviour test

8.4.1 Comparison with a reference measuring system (preferred)

The same records as taken in the test of 8.3.1 can be used and the relevant time parameters of the measured impulses evaluated for each system and the uncertainty of time parameters measured by the system under test shall be evaluated (5.11).

NOTE t_{min} may be chosen from one impulse type and t_{max} from another, for cases where approval is required for a group of impulse types. In such cases, the longest time to half-value of all the impulse types should be used.

8.4.2 Alternative method based on step response parameters (Annex C)

The system is subjected to a voltage step and the output is recorded. For the evaluation see Annex C.

NOTE Performance can be investigated using convolution techniques. The scale factor of the measuring system is established by any suitable method. The wave shape used to determine the scale factor should be within the range covered by the convolution method described in Annex D.

The dynamic behaviour is determined from the step response of the measuring system (recorded according to Annex C) and from convolution of the recorded step response with the nominal waveforms for which approval is sought. From the convolution, the errors introduced by the measuring system for different wave shapes can be estimated (Annex D). The change in scale factor over the reference level epoch shall be within ± 1 %.

8.5 Performance check

8.5.1 Comparison with an approved measuring system

A comparison is made with another approved measuring system (or reference measuring system) using the procedure of 5.2. For the comparison of peak values a sphere gap according to IEC 60052 may be used.

When the difference between the two measured peak values is not greater than 3 %, the assigned scale factor is taken as still valid. If it is greater, then a new value of the assigned scale factor shall be determined in a performance test.

The value of each time parameter shall be within ±10 % of the corresponding value measured by the other measuring system. When any difference is larger than 10 % then the nominal epoch shall be determined in a performance test.

8.5.2 Check of the scale factors of the components

The scale factor(s) of each component shall be checked using internal or external calibrators having expanded uncertainties of no more than 1 %. If the scale factors differ from their previous values by not more than ±1 % the assigned scale factor is taken as still valid. If any difference exceeds ±1 % a new value of the assigned scale factor shall be determined.

8.5.3 Dynamic behaviour check by reference record

When wanted for use in performance checks, the step response of the measuring system shall be recorded using the method of Annex C. This shall be included in the record of performance for use as a reference record ("fingerprint") to permit detection of changes in the dynamic behaviour at subsequent performance checks.

9 Measurement of switching impulse voltage

9.1 Requirements for an approved measuring system

9.1.1 General

The general requirements are:

- to measure the test voltage value according to IEC 60060-1 (peak value) of switching impulses with an expanded uncertainty $U_{M1} \leq 3$ %.
- to measure the time parameters which define the waveform with an expanded uncertainty $U_{M3} \leq 10$ %.

9.1.2 Uncertainty contribution

For a switching impulse voltage measuring system, the expanded uncertainty of measurement U_M shall be evaluated with a coverage probability of 95 %; according to 5.10.3, 5.11.3 and – if necessary - Annexes A and B. Tests for assessing contributions to uncertainty which are usually considered are summarized in Table 5. Other contributions can be important in some cases and shall be considered in addition.

9.1.3 Requirements for the measuring instrument

The measuring instrument shall comply with IEC 61083-1 and IEC 61083-2.

9.1.4 Dynamic behaviour

The dynamic behaviour of a measuring system is adequate when:

- the scale factor is constant within ±1 % over the range of impulse waveforms specified in the record of performance,
- the expanded uncertainty of the measured time parameters is not greater than 10 % over the range of waveforms.

9.1.5 Connection to the test object

The approved measuring system shall be connected directly to the terminals of the test object. In contrast to measurements of lightning impulse voltage (see 8.1.5), the measuring system may be interposed between the voltage source and the test object. The coupling between the test and measuring circuits should be negligible.

9.2 Tests on an approved measuring system

The tests according to Clause 5, summarized in Table 5, are necessary for the qualification of a switching impulse voltage measuring system and its components as well as for the estimation of the expanded uncertainty. For exceptions see 4.4.2

The results of the type and routine tests can be taken from manufacturer's data. Routine tests shall be performed on each unit.

9.3 Performance test on measuring systems

9.3.1 Reference method (preferred)

The assigned scale factor and the dynamic behaviour of the measuring system shall be determined by comparison with a reference measuring system using the procedure in 5.2. The performance over the nominal epoch t_{min} to t_{max} is proven by using impulses with two different waveforms such that:

- t_{min} is equal to the shortest time-to-peak T_{pmin}
- t_{max} is equal to the longest time-to-peak T_{pmax}
- both these waveforms should approximately have the longest time to half-value T_{2max} (or time above 90 % or time to zero) for which the measuring system is to be approved.

9.3.2 Alternative methods supplemented by a step response measurement

The assigned scale factor is determined by a comparative measurement waveform against a reference measuring system according to 5.2 using full impulses with one time to peak value T_{pcal} within the range T_{pmin} to T_{pmax} and a time to half-value (or time above 90 % or time to zero) approximately equal to the longest time to half-value (or time above 90 % or time to zero) for which the measuring system is to be approved. Alternatively it can be determined from the scale factors of the components (5.2.2).

In addition the step response of the measuring system shall be recorded according to Annex C. The reference level(s) of the reference level epoch(s) for which the measuring system is to be approved shall not differ from the value of the step response at T_{pcal} by more than ±1 %.

The step response shall not change by more than 5 % in the range from T_{pmin} to T_{2max} (or time above 90 % or time to zero) for which the measuring system is to be approved.

9.4 Dynamic behaviour test by comparison

The same records as taken in the test of 9.3.1 can be used and the relevant time parameters of the measured impulses evaluated for each system and the uncertainty of time parameters measured by the system under test shall be evaluated according to 5.4 (Table 5).

NOTE t_{min} may be chosen from one impulse type and t_{max} from another, for cases where approval is required for a group of impulse types. In such cases, the longest time to half-value of all the impulse types should be used.

9.5 Performance check

9.5.1 Scale factor check by comparison with an approved measuring system

A comparison is made with another approved measuring system (or reference measuring system) using the procedure of 5.2. For the comparison of peak values a sphere gap according to IEC 60052 may be used.

When the difference between the two measured peak values is not larger than 3 %, the assigned scale factor is taken as still valid. If it is larger, then a new value of the assigned scale factor shall be determined in a performance test.

The value of each time parameter shall be within ±10 % of the corresponding value measured by the other measuring system. When any difference is larger than 10 % then the nominal epoch shall be determined in a performance test.

9.5.2 Check of the scale factors of the components

The scale factor(s) of each component shall be checked using internal or external calibrators having expanded uncertainties of no more than 1 %. If the scale factors differ from their previous values by not more than ±1 % the assigned scale factor is taken as still valid. If any difference exceeds ±1 % a new value of the assigned scale factor shall be determined.

9.5.3 Dynamic behaviour check by reference record

When required for use in performance checks, the step response of the measuring system shall be recorded using the method of Annex C. This shall be included in the record of performance for use as a reference record ("fingerprint") to permit detection of changes in the dynamic behaviour at subsequent performance checks.

Table 5 – Tests required for a switching impulse voltage measuring system

Type of test	Type test	Routine test	Performance test	Performance check
Scale factor/time parameters at calibration			5.2 5.11/9.3	
Scale factor check				9.5
Linearity, see NOTE 2		5.3	5.3 (if applicable)	
Dynamic behaviour	5.4 9.4		5.4 9.4	9.5
Short-term stability		5.5		
Long-term stability	5.6		5.6 (if applicable)	
Ambient temperature effect	5.7			
Proximity effect, see NOTE 3	5.8 (if applicable)		5.8 (if applicable)	
Software effect (IEC 61083-2)	5.9 (if applicable)			
Interference test			5.12	5.12
Dry withstand test	5.13	5.13 (if required)		
Wet or polluted withstand test	5.13 (if required)			
Scale factor/time parameters of converting device	5.2.2	5.2.2		
Scale factor/time parameters of transmission system other than a cable	5.2.2	5.2.2		
Scale factor/time parameters of measuring instrument	5.2.2 IEC 61083	5.2.2 IEC 61083		
Responsibilities:	on components, by manufacturer		on the system, by user, see NOTE 1	
Recommended repetition rate:	only once (type and routine test)		Proposed annually, but at least every 5 years	according to stability, but at least annually

NOTE 1 The above listed tests should also be applied to the single components if performance tests are made according to the alternative method (see 5.2.2). To obtain the measuring uncertainty of the approved measuring system, those of the components should be combined as demonstrated in Annex B.

NOTE 2 A linearity test according to 5.3 is only required if the calibration cannot be performed by comparison over the full measurement range (5.2.1.2).

NOTE 3 Investigation of the proximity effect in the performance test is only necessary if the type test data are not sufficient

10 Reference measuring systems

10.1 Requirements for reference measuring systems

10.1.1 Direct voltage

The reference measuring system shall enable direct voltage measurement with an expanded uncertainty $U_M \leq 1$ % in its range of use. The uncertainty shall not be influenced by a ripple factor up to 3 %.

10.1.2 Alternating voltage

The reference measuring system shall enable alternating voltage measurement with an expanded uncertainty $U_M \leq 1$ % in its range of use.

10.1.3 Full and chopped lightning and switching impulse voltages

The reference measuring system shall enable full and tail-chopped impulse voltage measurement with an expanded uncertainty $U_{M1} \leq 1$ % for the peak values of full and tail-chopped impulses, $U_{M2} \leq 3$ % for the peak of front-chopped lighting impulses and $U_{M3} \leq 5$ % for the time parameters in its range of use.

NOTE Oscillations and/or overshoot should be recorded adequately (compare with 8.1.4).

10.2 Calibration of a reference measuring system

10.2.1 General

The compliance of a reference measuring system with the relevant requirements given in 10.1 shall be shown by the test of 10.2.2. Alternatively the test of 10.2.3 may be used.

10.2.2 Reference method: Comparative measurement

The satisfactory performance of a reference measuring system shall be shown by calibration by comparison measurements at the relevant test voltage against a low-uncertainty reference measuring system, which is itself traceable to the standards of a National Metrological Institute.

In case of impulse voltages, waveforms of two or more different front times covering the range of the nominal epoch shall be applied.

NOTE The requirements for a low-uncertainty reference measuring system should be expanded uncertainties $U_M \leq 0,5$ % for voltage measurement and – for impulse voltages only - $U_{M3} \leq 3$ % for time parameter measurement.

10.2.3 Alternative method for impulse voltages: Measurement of scale factor and evaluation of step response parameters

The scale factor of a reference measuring system shall be established for one impulse voltage shape e.g. by means of a higher class reference measuring system at the relevant test voltage. Additionally step response parameters evaluated according to Annex C shall satisfy the recommendations of Table 6. Additionally the reference level(s) of the reference level epoch(s) for which the reference measuring system is to be approved shall not differ from the value of the step response at the time of the relevant parameter of the used impulse voltage by more than ±0,5 %.

10.3 Interval between successive calibrations of reference measuring systems

The interval between calibrations shall be determined according to national regulations. If there is no regulation it is recommended that the calibrations shall be repeated at least once every five years, provided that regular performance checks demonstrate the stability of the reference measuring system.

10.4 Use of reference measuring systems

It is recommended that reference measuring systems should be used only for comparative measurements in performance tests. However, reference measuring systems may be used for other measurements, including routine daily use, if it is shown that such use does not affect their performance (The performance checks specified in this standard are sufficient to verify this). In addition, the substitution of an equivalent measuring instrument, which satisfies the relevant IEC standard, shall be accepted.

Table 6 – Recommended response parameters for impulse voltage reference measuring systems

	Recommendations for		
Voltage	**Full and tail-chopped lightning impulses**	**Front-chopped lightning impulses**	**Switching impulses**
Experimental response time T_N	≤ 15 ns	≤ 10 ns	-
Settling time t_s	≤ 200 ns	≤ 150 ns	≤ 10 µs
Partial response time T_α	≤ 30 ns	≤ 20 ns	-

Annex A
(informative)

Uncertainty of measurement

A.1 General

Clause 5 describes a simplified procedure to evaluate the uncertainty of measurement under conditions usually applicable and fully sufficient in high-voltage measurement. In some cases it may, however, be necessary or desirable to evaluate uncertainties in a more complex manner. Annex A gives a survey on how to proceed in these cases, and Annex B describes three application examples.

Each measurement of a quantity is to some degree imperfect, and the result of a measurement is only an approximation ("estimate") of the "true" value of the measurand. The uncertainty of measurement makes a clear statement on the quality of a measurement. It enables the user to compare and weight the measurement results, e.g. obtained from different laboratories, and it provides information as to whether or not a measurement result is within the limits specified by a standard. A Guide to the expression of Uncertainty in Measurement (GUM) originally published in 1993 by the International Organization for Standardization (ISO) now exists as ISO/IEC 98-3: 2008 is the internationally accepted standard for the estimation of measurement uncertainty.

ISO/IEC Guide 98-3 as a guide provides general rules for evaluating and expressing uncertainty in a broad spectrum of measurements at various levels of uncertainty. It is therefore necessary to extract from the ISO/IEC Guide 98-3 a set of specific rules that deals with the specific field of high-voltage measurement and its level of accuracy and complexity. Corresponding to the basic principles of the ISO/IEC Guide 98-3, uncertainties are grouped into two categories according to their methods of evaluation. Both methods are based on probability distributions of the quantities influencing the measurement and on standard uncertainties quantified by variances or standard deviations. This allows a uniform treatment of both categories of uncertainties and an evaluation of a combined standard uncertainty of the measurand. Within the scope of this standard, an expanded uncertainty corresponding to a coverage probability of approximately 95 % is required.

The basic principles of the ISO.IEC Guide 98-3 and examples of how to determine uncertainties in high voltage measurements are presented in the following clauses. The equations and examples given here are valid for uncorrelated input quantities, which is often the case in high-voltage measurements.

A.2 Definitions in addition to Clause 3

A.2.1
measurable quantity
attribute of a phenomenon, body or substance that may be distinguished qualitatively and determined quantitatively

A.2.2
value of a quantity
magnitude of a particular quantity generally expressed as unit of measurement multiplied by a number

A.2.3
measurand
specific quantity subjected to measurement

A.2.4
variance
expectation of the square of the deviation of a random variable in terms of its expectation

A.2.5
correlation
relationship between two or several random variables within a distribution of two or more random variables

A.2.6
coverage probability
fraction, usually large, of the distribution of values that as a result of a measurement could reasonably be attributed to the measurand

A.3 Model function

Each measurement can be described by a functional relationship f:

$$Y = f\left(X_1, X_2, \ldots, X_i, \ldots, X_N\right) \tag{A.1}$$

where Y is the measurand and X_i are the different input quantities numbered from 1 to N. In the meaning of the ISO/IEC GUIDE 98-3 the model function f comprises all measurement values, influencing quantities, corrections, correction factors, physical constants, and any other data that can contribute a significant amount to the value of Y and its uncertainty. It may exist as a single or manifold analytical or numerical expression, or a combination of both. In general the input quantities X_i are random variables and described by observations x_i ("input estimates") having specific probability distributions and being associated with standard uncertainties $u(x_i)$ of Type A or Type B. The combination of both types of uncertainty according to the rules of the ISO/IEC GUIDE 98-3 yields the standard uncertainty $u(y)$ of the output estimate y.

NOTE 1 The model function f in Equation (A.1) is also valid for the input and output estimates x_i and y, respectively.

NOTE 2 In a series of observations, the k'th observed value of the quantity X_i is denoted x_{ik}.

A.4 Type A evaluation of standard uncertainty

The evaluation method of Type A is applied to quantities that vary randomly and for which n independent observations have been obtained under the same conditions of measurement. In general, a normal (Gaussian) probability distribution of the n observations x_{ik} can be assumed (Figure A.1).

NOTE 1 X_i might be a scale factor, a test voltage value or a time parameter with the observations x_{ik}.

The arithmetic mean value $\bar{x}_i$ of the observations x_{ik} is defined by

$$\bar{x}_i = \frac{1}{n}\sum_{k=1}^{n}\bar{x}_{ik} \ , \tag{A.2}$$

which is considered to be the best estimate of X_i. Its Type A standard uncertainty is equal to the experimental standard deviation of the mean:

$$u(\bar{x}_i) = s(\bar{x}_i) = \frac{s(x_i)}{\sqrt{n}} \tag{A.3}$$

where $s(x)$ is the experimental standard deviation (of the individual values):

$$s(x_i) = \sqrt{\frac{1}{n-1}\sum_{k=1}^{n}(x_{ik} - \bar{x}_i)^2} \tag{A.4}$$

The quadratic values of $s^2(x_i)$ and $s^2(\bar{x}_i)$ are called sample variances and variances of the mean, respectively. The number of observations should be $n \geq 10$, otherwise the reliability of a Type A evaluation of standard uncertainty has to be checked by means of the effective degrees of freedom (see Clause A.8).

NOTE 2 In some cases a pooled estimate of variance s_p^2 may be available from a large number of previous observations under well-defined conditions. Then the standard uncertainty of a comparable measurement with a small number n (n = 1, 2, 3, ...) is better estimated by $u(\bar{x}_i) = s_p / \sqrt{n}$ than by Equation (A.3).

A.5 Type B evaluation of standard uncertainty

The evaluation method of Type B applies to all cases other than the statistical analysis of a series of observations. The standard uncertainty of Type B is evaluated by scientific judgment based on all available information on the possible variability of an input quantity X_i with observations x_i, such as:

- method of evaluating quantities,
- uncertainty of calibration of the measuring system and its components,
- non-linearity of dividers and measuring instruments,
- dynamic behavior, e. g. scale factor variation with frequency or impulse shape,
- short-term stability, self-heating,
- long-term stability, drift,
- ambient conditions during measurement,
- proximity effect of nearby objects,
- effects caused by software used in instruments or in evaluation of results,
- limited resolution of digital instruments, reading of analogue instruments,

Information on input quantities and uncertainties can be obtained from actual and previous measurements, calibration certificates, data in handbooks and standards, manufacturer's specifications or knowledge of the characteristics of relevant materials or instruments. The following cases of a Type B evaluation of uncertainties can be identified:

a) Often only a single input value x_i and its standard uncertainty $u(x_i)$ is known, e.g. a single measured value, a correction value or a reference value from literature. This value and its uncertainty will be adopted in the model function Equation (A.1). In case $u(x_i)$ is unknown, it shall be calculated from other relevant uncertainty data or be estimated on the basis of experience.

b) The uncertainty of a device is quoted as a standard uncertainty multiplied by the coverage factor k, e.g. the expanded standard uncertainty U of a digital voltmeter in a calibration certificate (Clause A.7). When the voltmeter is used in a complex measuring system it contributes to uncertainty by:

$$u(x_i) = \frac{U}{k} \tag{A.5}$$

where k is the coverage factor. Instead of expressing the expanded uncertainty and coverage factor, one may find a statement on the confidence level, e.g. 68,3 %, 95,45 % or 99,7 %. In general, a normal distribution according to Figure A.1 can be assumed and the statement on the confidence level is equivalent to the coverage factor k = 1, 2 or 3, respectively.

c) The value x_i of an input quantity X_i is estimated to lie within the interval a_- to a_+ with a certain probability distribution $p(x_i)$. Often there is no specific knowledge of $p(x_i)$ and a rectangular distribution of the probable values is then assumed (Figure A.2). Then the expected value of X_i is the midpoint $\overline{x_i}$ of the interval:

$$\overline{x_i} = \frac{(a_- + a_+)}{2} \tag{A.6}$$

and the associated standard uncertainty:

$$u(x_i) = \frac{a}{\sqrt{3}} \tag{A.7}$$

where $a = (a_+ - a_-)/2$.

In some cases other probability distributions may be more appropriate, such as trapezoidal, triangular or normal distributions.

NOTE 1 The standard uncertainty is $u(x_i) = a/\sqrt{6}$ for the triangular distribution and $u(x_i) = \sigma$ for the normal distribution. This means that the rectangular distribution yields a larger standard uncertainty than the other distributions.

The ISO/IEC Guide 98-3 states that a Type B uncertainty should not be double-counted if the particular effect has already contributed to a Type A uncertainty. Furthermore, the evaluation of uncertainty should be realistic and based on standard uncertainties, avoiding the use of personal or any other factors of safety to obtain larger uncertainties than those evaluated according to the ISO/IEC GUIDE 98-3. Often an input quantity X_i has to be adjusted or corrected to eliminate systematic effects of significant magnitude, e.g. on the basis of a temperature or voltage dependence. However, the uncertainty $u(x_i)$ associated with this correction shall still be taken into account.

NOTE 2 Double-counting of uncertainty contributions may occur when a digital recorder is used for repetitive impulse measurements, e.g. when calibrating the scale factor. The dispersion of the n measurement values producing a Type A standard uncertainty may be partially caused by a limited resolution of the recorder and its internal noise. The resolution does not need to be considered again, in full, but rather only in a small portion as a residual Type B uncertainty. However, if the digital recorder is then used during an impulse voltage test to obtain a single measurement value, the limited resolution needs to be considered in a Type B uncertainty.

NOTE 3 The evaluation of Type B uncertainties requires extensive knowledge and experience of the relevant physical relationships, influence quantities and measurement techniques. As the evaluation itself is not an exact science leading to one single solution, it is not uncommon that experienced test engineers may judge the measurement process in a different manner and obtain different Type B uncertainty values.

A.6 Combined standard uncertainty

Each standard uncertainty $u(x_i)$ of the estimate x_i each input quantity X_i evaluated by method Type A or Type B contributes to the standard uncertainty of the output quantity by:

$$u_i(y) = c_i\, u(x_i) \tag{A.8}$$

where c_i is the sensitivity coefficient. It describes how the output estimate y is influenced by small variations of the input estimate x_i. It can be evaluated directly as the partial derivative of the model function f:

$$c_i = \frac{\partial f}{\partial X_i}\Big|_{X_i = x_i} = \frac{\partial f}{\partial x_i}, \quad \text{(A.9)}$$

or by using equivalent numerical and experimental methods. The sign of c_i may be positive or negative. In cases where input quantities are uncorrelated, the sign need not be considered further since only the quadratic value of standard uncertainties is used in the next steps.

The N standard uncertainties $u_i(y)$ defined by Equation (A.8) contribute to a combined standard uncertainty $u_c(y)$ of the output quantity according to the "law of propagation of uncertainty":

$$u_c^2(y) = u_1^2(y) + u_2^2(y) + \ldots + u_N^2(y) = \sum_{i=1}^{N} u_i^2(y) \quad \text{(A.10)}$$

from which $u_c(y)$ is evaluated as the positive square root:

$$u_c(y) = \sqrt{\sum_{i=1}^{N} u_i^2(y)} = \sqrt{\sum_{i=1}^{N} [c_i\, u(x_i)]^2} \quad \text{(A.11)}$$

If the output quantity Y is a product or quotient of the input quantities X_i a similar relationship as shown in Equations (A.10) and (A.11) can be obtained for the relative uncertainties $u_c(y)/|y|$ and $u(x_i)/|x_i|$. The law of propagation of uncertainty thus applies to both types of the model function for uncorrelated input quantities.

NOTE In a case where correlation exists, linear terms will be present in the law of propagation of uncertainty, and the sign of the sensitivity coefficients becomes relevant. Correlation occurs when, for example, the same instrument is used for measuring two or more input quantities. To avoid complicated calculation, the correlation can be removed by adding additional input quantities in the model function f with appropriate corrections and uncertainties. In some cases, the presence of correlated input quantities may even reduce the combined uncertainty. Taking correlation into account is thus mainly essential for sophisticated uncertainty analysis to achieve a very accurate estimation of uncertainty. Correlation will not be discussed further in this standard.

A.7 Expanded uncertainty

In the field of high-voltage and high-current measurements, as in most other industrial applications, a statement of uncertainty corresponding to a coverage probability of approximately p = 95 % is required. This is achieved by multiplying the combined standard uncertainty $u_c(y)$ in (A.11) by a coverage factor k:

$$U = k u_c(y), \quad \text{(A.12)}$$

where U is the expanded uncertainty. The coverage factor k = 2 is used in cases where a normal distribution can be attributed to y and $u_c(y)$ has sufficient reliability, i.e. the effective degrees of freedom of $u_c(y)$ is sufficiently large (see Clause A.8). Otherwise a value $k > 2$ has to be determined to obtain p = 95 %.

NOTE 1 In some older standards the term "overall uncertainty" is used. In the majority of cases this term is interpreted as an expanded uncertainty U with the coverage factor being equal to 2.

NOTE 2 Since uncertainties are defined as positive numbers, the sign of U is always positive. Of course, in cases where U is used in the meaning of an uncertainty interval, it is quoted k as $\pm U$.

A.8 Effective degrees of freedom

The assumption of a normal distribution of the expanded uncertainty is, in general, fulfilled in cases where several (i.e. $N \geq 3$) uncertainty components of comparable value and well-defined probability distribution (Gaussian, rectangular, etc.) contribute to the combined standard uncertainty and where the Type A uncertainty is based on $n \geq 10$ repeated observations. These conditions are fulfilled in many calibrations of voltage measuring systems. When the assumption of a normal distribution is not justified, a value of $k > 2$ shall be evaluated to obtain a coverage probability of approximately 95 %. The appropriate coverage factor can be evaluated on the basis of the effective degrees of freedom ν_{eff} of the standard uncertainty $u_{\text{c}}(y)$:

$$\nu_{\text{eff}} = \frac{u_{\text{c}}^4(y)}{\sum_{i=1}^{N} \frac{u_{\text{i}}^4(y)}{\nu_{\text{i}}}}, \tag{A.13}$$

where $u_{\text{i}}(y)$ is given by Equation (A.8) for $i = 1, 2, \ldots, N$ and ν_{i} is the corresponding degrees of freedom. Reliable values of ν_{i} are as follows:

$\nu_{\text{i}} = n - 1$ for a Type A uncertainty based on n independent observations,

$\nu_{\text{i}} \geq 50$ for a Type B uncertainty taken from a calibration certificate, and when the coverage probability is stated to be not less than 95 %,

$\nu_{\text{i}} = \infty$ for a Type B uncertainty assuming a rectangular distribution within a_- and a_+

The effective degrees of freedom can then be calculated by Equation (A.13) and the coverage factor be taken from Table A.1 which is based on a *t*-distribution evaluated for a coverage probability of $p = 95{,}45$ %. If ν_{eff} is not an integer interpolate or truncate ν_{eff} to the next lower integer.

Table A.1 – Coverage factor k for effective degrees of freedom ν_{eff} ($p = 95{,}45$ %)

ν_{eff}	1	2	3	4	5	6	7	8	10	20	50	∞
k	13,97	4,53	3,31	2,87	2,65	2,52	2,43	2,37	2,28	2,13	2,05	2,00

The following formula can also be used to calculate k from ν_{eff}:

$$k = 1{,}96 + \frac{2{,}374}{\nu_{\text{eff}}} + \frac{2{,}818}{\nu_{\text{eff}}^2} + \frac{2{,}547}{\nu_{\text{eff}}^3} \tag{A.14}$$

A.9 Uncertainty budget

The uncertainty budget of a measurement is a detailed analysis of all sources and values of uncertainty according to the model function f. The relevant data should be kept for inspection in the form of a table equal or comparable to Table A.2. The last line indicates the values of the measurement result y, the combined uncertainty $u_{\text{c}}(y)$ and the effective degrees of freedom ν_{eff}.

Table A.2 – Schematic of an uncertainty budget

Quantity X_i	Value x_i	Standard uncertainty contribution $u(x_i)$	Degrees of freedom v_i / v_{eff}	Sensitivity coefficient c_i	Contribution to combined standard uncertainty $u_i(y)$
X_1	x_1	$u(x_1)$	v_1	c_1	$u_1(y)$
X_2	x_2	$u(x_2)$	v_2	c_2	$u_2(y)$
:	:	:	:	:	:
X_N	x_N	$u(x_N)$	v_N	c_N	$u_N(y)$
Y	y		v_{eff}		$u_c(y)$

NOTE Validated software is commercially available or may be developed by the user from general software that enables automated calculation of the quantities in Table A.2 from the model equation f.

A.10 Statement of the measurement result

In calibration and test certificates the measurand Y shall be expressed as $y \pm U$ for a coverage probability (or: level of confidence) of approximately p = 95 %. The numerical value of the expanded uncertainty U shall be rounded to give not more than two significant figures. If rounding down reduces the value by more than 0,05 U, the rounded-up value shall be used. The numerical value of y shall be rounded to the least significant figure that could be affected by the expanded uncertainty.

NOTE 1 As an example, the result of a voltage measurement is stated in one of the following ways:

(227,2 ± 2,4) kV,

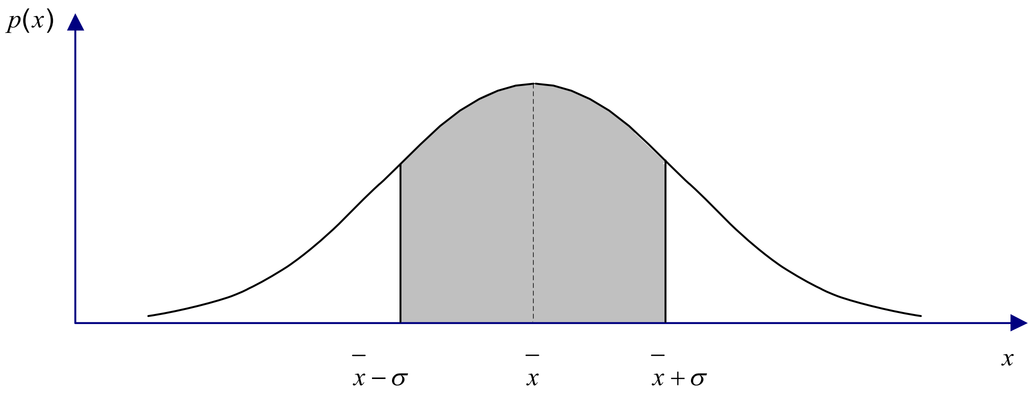
227,2 × (1 ± 0,011) kV, or

227,2 × (1 ± $1{,}1 \cdot 10^{-2}$) kV.

An explanatory note should be added informing of the coverage probability p and the coverage factor k.

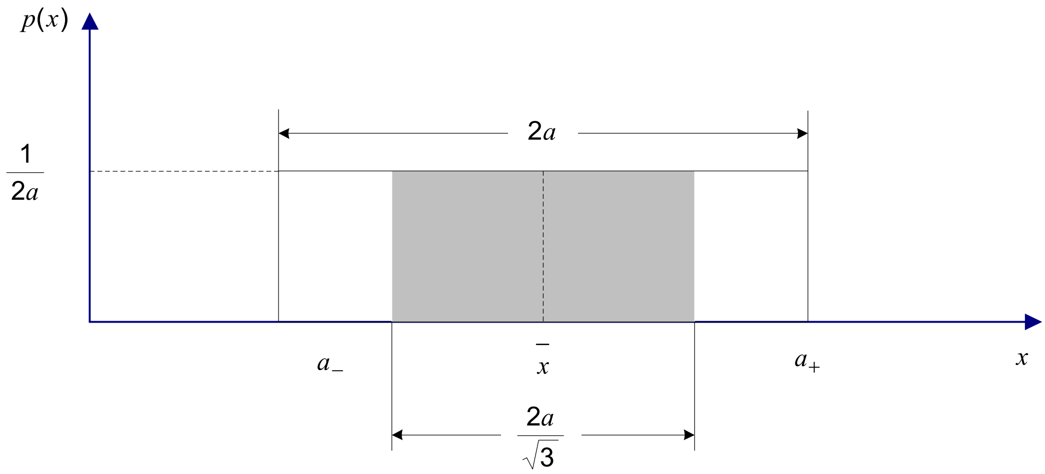
NOTE 2 As an example, the following complete wording is recommended (the terms in brackets apply to the cases where v_{eff} < 50, i.e. k > 2,05 according to Table A.1):

"The reported expanded uncertainty of measurement is stated as the uncertainty of measurement multiplied by the coverage factor k = 2 (k = XX), which for a normal distribution (t-distribution with v_{eff} = YY effective degrees of freedom) corresponds to a coverage probability of approximately 95 %. The standard uncertainty of measurement has been determined in accordance with IEC 60060-2."



NOTE Shaded area indicates the standard uncertainty above and below $\bar{x}_i$.

Figure A.1 – Normal probability distribution $p(x)$



NOTE Shaded area indicates the standard uncertainty above and below $\bar{x}_i$.

Figure A.2 – Rectangular probability distribution $p(x)$

Annex B
(informative)

Examples for the calculation of measuring uncertainties in high-voltage measurements

B.1 Example 1: Scale factor of an AC measuring system (comparison method)

An AC measuring system of rated voltage 500 kV, denoted by X, is calibrated by an accredited calibration laboratory in the test laboratory of the customer. The calibration is performed up to V_{Xmax} = 500 kV by comparison with a reference measuring system, denoted by N (Figure B.1). Both systems consist of a divider and a digital voltmeter, indicating the voltage values V_N and V_X, respectively, at the divider outputs. The scale factor and the relative expanded uncertainty of the reference system N at 20 °C is F_N = 1,025 and U_N = 0,8 % (k=2), including an uncertainty contribution estimated for the long-term instability.

During the calibration, ambient temperature is (15 ± 2) °C. Since the scale factor of N was calibrated at 20 °C, it is corrected by -0,3 % according to its temperature coefficient, yielding the actual value F_N = 1,022 at 15 °C. This correction, however, is not very accurate and, furthermore, due to the temperature variation within ±2 °C during the calibration, the probable values of F_N are assumed to lie within an interval of ±0,001 around F_N with rectangular distribution. The comparison measurements are performed at h = 5 voltage levels of about 20 %, 40 %, ... 100 % of V_{Xmax}. At each voltage level, simultaneous readings of the voltages V_N and V_X are taken for n = 10 voltage applications. Further investigations on the dynamic behaviour, short-term stability, temperature interval, and interference show an influence on the scale factor of the test object, F_X, within ±0,2 % each. Its long-term stability is estimated on the basis of the manufacturer's data to lie within ±0,3 % until the next calibration.

The model equation for calculating the value of F_X and its combined standard uncertainty can be developed as follows. In the ideal case, both measuring systems indicate the same value of the AC test voltage V (Figure B.1):

$$V = F_N V_N = F_X V_X \tag{B.1}$$

This leads to the basis equation for calculating the scale factor of the system under test:

$$F_X = \frac{V_N}{V_X} F_N \tag{B.2}$$

As described above, the scale factors of both systems are subject to several influence quantities such as drift, temperature, etc. They contribute to the scale factor values and their uncertainties as well. These contributions are denoted here by $\Delta F_{N,1}$, $\Delta F_{N,2}$, ... for the reference system, and by $\Delta F_{X,1}$, $\Delta F_{X,2}$, ... for the system under test. In general, each contribution to the scale factor F_N or F_X consists of an error and a standard uncertainty. The error is taken to correct the scale factor, the correction being of opposite sign. The uncertainty contribution is related to the relevant scale factor F_N or F_X and evaluated in a similar way as described in Clause A.5, i.e., either by assuming a rectangular probability distribution within an interval $\pm a_i$, leading to a standard uncertainty $u_i = a_i/\sqrt{3}$, or, in the case of a calibrated component, by dividing its expanded uncertainty U by the coverage factor k. The contribution $\Delta F_{N,m}$ or $\Delta F_{X,i}$ need not always have an error (or the error is assumed to be negligibly small), and then it consists only of the uncertainty contribution u_i.

The basis equation (B.2) is supplemented by the contributions $\Delta F_{N,m}$ and $\Delta F_{X,i}$ to obtain the complete model function for determining the scale factor F_X and its combined standard uncertainty. Since correlation between the influence quantities is neglected, Equation (B.2) can then be written in the general version:

$$F_X - \sum_i \Delta F_{X,i} = \frac{V_N}{V_X}\left(F_N - \sum_m \Delta F_{N,m}\right). \tag{B.3}$$

NOTE 1 As per definition, the errors inserted on both sides of the equation have a negative sign. They are defined as ΔF = (indicated value) – (correct value).

For the relevant case, the scale factor F_X of the AC measuring system can be expressed by:

$$F_X = \frac{V_N}{V_X}\left(F_N - \Delta F_N\right) + \sum_{i=1}^{5} \Delta F_{X,i}\ , \tag{B.4}$$

where:

ΔF_N is the contribution caused by the lower temperature of the reference system,

$\Delta F_{X,1}$ is the contribution caused by the nonlinearity of the quotient,

$\Delta F_{X,2}$ is the contribution caused by the short-term instability of the system under test,

$\Delta F_{X,3}$ is the contribution caused by the long-term instability of the system under test,

$\Delta F_{X,4}$ is the contribution caused by the dynamic behaviour of the system under test,

$\Delta F_{X,5}$ is the contribution caused by the temperature variation of the system under test.

NOTE 2 In this example, ΔF_N consists both of a correction and an uncertainty contribution to the scale factor F_N, whereas the terms ΔF_{X1} to ΔF_{X5} contribute only to the uncertainty of the scale factor F_X. For convenience, the uncertainty contributions ΔF_{X1} to ΔF_{X5} are directly related to F_X, i.e. the sensitivity coefficients of these input quantities have already been taken into consideration.

The comparison measurement at a single voltage level between the measuring system X and the reference system N yields n = 10 pairs of measured values V_N and V_X, from which the quotients V_N/V_X, their mean and the experimental standard deviation $s(V_N/V_X)$ are calculated. An example for the values measured at a voltage level of about 40 % V_{Xmax} is given in Table B.1. In the same manner, the quotients V_N/V_X and standard deviations $s(V_N/V_X)$ are obtained for a total of h = 5 voltage levels up to 500 kV (Table B.2).

Table B.1 – Result of the comparison measurement at a single voltage level

Number of measurement	**Reference System** V_N **kV**	**System under test** V_X **V**	**Quotient** V_N/V_X
1	191,4	190,8	1003,1
2	191,6	190,9	1003,7
3	190,7	189,9	1004,2
4	189,9	189,0	1004,8
5	190,9	189,9	1005,3
6	191,2	190,3	1004,7
7	191,3	190,4	1004,7
8	191,2	190,4	1004,2
9	190,6	189,9	1003,7
10	191,3	190,7	1003,1
Mean of V_N/V_X at about 40 % V_{Xmax}			**1004,2**
Experimental standard deviation $s(V_N/V_X)$:			**0,73**

Table B.2 – Summary of results for h = 5 voltage levels (V_{Xmax} = 500 kV)

g No.	Voltage level % of V_{Xmax}	V_N/V_X	$s(V_N/V_X)$
1	18	1003,2	0,71
2	38	1004,2	0,73
3	63	1004,5	0,81
4	83	1006,5	0,68
5	100	1010,1	**0,85** (= s_{max})
Mean		**1005,7**	

The mean of the five quotients V_N/V_X in Table B.2 is 1005,7. To be on the safe side of the uncertainty estimation, the Type A standard uncertainty of V_N/V_X is evaluated from the maximum standard deviation s_{max} = 0,85 according to Equation (A.3):

$$u_A = \frac{s_{max}}{\sqrt{n}} = \frac{0{,}85}{\sqrt{10}} = 0{,}27$$

The deviation of the quotients V_N/V_X from their mean characterises the nonlinearity of system X. The maximum deviation is a_1 = 4,4 at 100 % of V_{Xmax} (Table B.2). The Type B standard uncertainty of V_N/V_X, originating from nonlinearity, is thus $a_1/\sqrt{3}$ = 2,54 according to Equation (A.7). This value is multiplied by the relevant sensitivity coefficient $c_1 = \partial F_X/\partial(V_N/V_X) = F_N - \Delta F_N$ = 1,022 to obtain the Type B uncertainty contribution:

$$u_{B1} = \frac{a_1}{\sqrt{3}}\left(F_N - \Delta F_N\right) = \frac{4{,}4}{\sqrt{3}} 1{,}022 = 2{,}6$$

The values and standard uncertainties of all input quantities are entered on the right side of the model equation (B.4). The model equation can be evaluated manually, using the equations given in Annex A, or with the aid of special software which should be validated for calculating uncertainties. The result of the evaluation is summarized in Table B.3. In the last line, the assigned scale factor F_X, its combined standard uncertainty, and the effective degrees of freedom are given. The large value ν_{eff} = 180 indicates normal distribution of the probable values of F_X, and thus k = 2 is valid (see Annex A, Table A.1).

NOTE 3 The estimate of uncertainty is not very precise and high numerical precision is not required.

Finally, the complete result of the calibration of the approved measuring system is expressed by the assigned scale factor and its expanded uncertainty:

F_X = 1028 ± 11 = 1028(1 ± 0,011) for a coverage probability of not less than 95 % (k = 2).

The relative expanded uncertainty of the assigned scale factor is U = 1,1 %. Since it contains an uncertainty contribution of the long-term stability, it can be applied as the expanded uncertainty of the test voltage until the next calibration of the approved measuring system, provided the stability of the scale factor is checked by intermediate performance checks (see 4.3).

NOTE 4 The simplified method of Clause 5 delivers an identical relative expanded uncertainty of the assigned scale factor.

Table B.3 – Uncertainty budget of the assigned scale factor F_X

Quantity	Value	Standard uncertainty contribution	Degrees of freedom	Sensitivity coefficient	Contribution to combined standard uncertainty
F_N	1,025	0,004 [1)]	50	1005,7	4,0
ΔF_N	0,003	0,000577 [2)]	∞	-1005,7	-0,58
V_N/V_X	1005,7	0,27 [1)]	9	1,022	0,28
$\Delta F_{X,1}$	0	2,60 [2)]	∞	1	2,6
$\Delta F_{X,2}$	0	1,19 [2)]	∞	1	1,2
$\Delta F_{X,3}$	0	1,78 [2)]	∞	1	1,8
$\Delta F_{X,4}$	0	1,19 [2)]	∞	1	1,2
$\Delta F_{X,5}$	0	1,19 [2)]	∞	1	1,2
F_X	**1027,8**		**180**		**5,54**

[1)] Normal distribution.

[2)] Rectangular distribution.

B.2 Example 2: Scale factor of an impulse voltage measuring system (component method)

The system for measuring lightning impulse voltages consists of an impulse divider of rated voltage 1,2 MV, a 10 bit digital recorder, and a 20 m coaxial cable. The scale factors of the impulse divider (index "div") and the digital recorder (index "rec") and their expanded uncertainties are stated by the manufacturers as:

F_{div} = 2015 (U_{div} = 1,2 %, $p \geq 95$ %, $k = 2$), and

F_{rec} = 1,050 (U_{rec} = 0,8 %, $p \geq 95$ %, $k = 2$).

The uncertainty of the divider comprises the contributions of the linearity test up to 1,2 MV, the dynamic behaviour and short-term stability. Additional information on the proximity effect and long-term stability is given by the manufacturer. The calibration of the digital recorder was made in all ranges between 60 % and 100 % of full scale deflection by applying smooth calibration impulses according to IEC 61083-1. The recorder's step response is rather flat, and it can be concluded that the scale factor does not depend on the time parameters within the tolerances specified for lightning impulse voltages.

In order to obtain the uncertainty of the complete measuring system, the user has to consider additional uncertainty contributions, either taken from the records of performance of the divider and recorder, or determined by additional tests. The following influencing quantities are assumed to have a rectangular distribution, the half-width being a_i, from which the uncertainty contributions are calculated as $a_i/\sqrt{3}$. The yearly long-term instability is specified by the manufacturer to be within ±0,3 % for the divider and ±0,2 % for the recorder. The short-term instability of the recorder is within ±0,3 %. The proximity effect need not be investigated as the divider is located outside the minimum clearance specified by the manufacturer. As the lightning impulses, generated in the user's test hall, are superimposed by oscillations of about 2 %, a residual deviation within ±0,3 % is attributed to the software of the recorder, used to calculate the peak value of the base curve according to the frequency dependent *k* factor (see IEC 60060-1, Clause 8).

The basis model equation to determine the assigned scale factor F of the complete measuring system is:

$$F = F_{\text{div}} \cdot F_{\text{rec}} \tag{B.5}$$

The model equation is supplemented - similar to Example B.1 - by additional terms $\Delta F_{\text{div,i}}$ and $\Delta F_{\text{rec,i}}$ caused by the influence quantities mentioned above. These terms generally consist of an error and a standard uncertainty $a_i/\sqrt{3}$ calculated from the half-width a_i of the probable values under the assumption of a rectangular probability distribution. The complete model function for the scale factor F_m of the complete measuring system reads:

$$F = \left(F_{\text{div}} - \Delta F_{\text{div}}\right) \cdot \left(F_{\text{rec}} - \sum_{i=1}^{3} \Delta F_{\text{rec,i}}\right) \tag{B.6}$$

where:

ΔF_{div} is the contribution caused by the long-term instability of the divider;

$\Delta F_{\text{rec,1}}$ is the contribution caused by the long-term instability of the recorder;

$\Delta F_{\text{rec,2}}$ is the contribution caused by the short-term instability of the recorder;

$\Delta F_{\text{rec,3}}$ is the contribution caused by the recorder's software (implementation of k factor).

NOTE 1 By definition, the errors ΔF_{div} and $\Delta F_{\text{rec,i}}$ have a negative sign. They are defined as ΔF = (indicated value) – (correct value).

NOTE 2 In this example, ΔF_{div} and the terms $\Delta F_{\text{rec,1}}$ to $\Delta F_{\text{rec,3}}$ contribute only to the uncertainty of scale factor F.

The values and standard uncertainties of all input quantities are entered on the right side of the model equation (B.6). The model equation can be evaluated manually, using the equations given in Annex A, or with the aid of special software which should be validated for calculating uncertainties. The result of the evaluation is summarised in Table B.4. In the last line, the assigned scale factor F of the complete measuring system, its combined standard uncertainty and the effective degrees of freedom are given.

NOTE 3 The estimate of uncertainty is not very precise and high numerical precision is not required.

Table B.4 – Uncertainty budget of the assigned scale factor F

Quantity	Value	Standard uncertainty contribution	Degrees of freedom	Sensitivity coefficient	Contribution to combined standard uncertainty
F_{div}	2015	12,1 [1)]	50	1,05	13
ΔF_{div}	0	3,49 [2)]	∞	-1,05	-3,7
F_{rec}	1,050	0,0042 [1)]	50	2015	8,5
$\Delta F_{\text{rec,1}}$	0	0,00121 [2)]	∞	-2015	-2,4
$\Delta F_{\text{rec,2}}$	0	0,00182 [2)]	∞	-2015	-3,7
$\Delta F_{\text{rec,3}}$	0	0,00182 [2)]	∞	-2015	-3,7
$\boldsymbol{F}$	**2115,8**		**130**		**16,7**

[1)] Normal distribution.

[2)] Rectangular distribution

The complete result for the assigned scale factor of the impulse measuring system is expressed by:

F = 2116 ± 33 = 2116(1 ± 0,016) for a coverage probability of not less than 95 % (k = 2).

The relative expanded uncertainty of the assigned scale factor is U = 1,6 %. Since it contains uncertainty contributions of the long-term stability for one year, it can be applied as the expanded uncertainty of the test voltage until the next calibration of the divider and recorder within 1 year.

B.3 Example 3: Front time of lightning impulse voltages

The front time of a 2 MV impulse voltage measuring system X, consisting of a divider and a digital recorder (10 bit, 100 MS/s), is calibrated by comparison with a reference measuring system N at lightning impulses of about 500 kV (Figure B.1). The systematic mean error of N for measuring front times is ΔT_{1N} = 0,01 μs in the nominal epoch, the expanded uncertainty being U_N = 0,02 μs (k = 2).

By the comparison, n = 10 lightning impulse voltages, having a specified front time, are recorded simultaneously with both systems. The actual front time of the i^{th} impulse voltage, recorded with system N, is determined by:

$$T_{1N,i} = (t_{90} - t_{30})/0{,}6, \tag{B.7}$$

where t_{30} and t_{90} denote the times at 30 % and 90 %, respectively, of the peak value evaluated with system N. The front time $T_{1X,i}$ of the same impulse voltage, recorded with system X, is calculated in the same manner.

From the n = 10 differences of the front times, measured with X and N each, the mean front time deviation, ΔT_1, is evaluated by:

$$\Delta T_1 = \frac{1}{10}\sum_{i=1}^{n}\left(T_{1X,i} - T_{1N,i}\right) \tag{B.8}$$

The comparison is performed for three different front times: the maximum, minimum and medial values of the nominal epoch, i.e. for T_1 ≈ 0,8 μs, ≈1,2 μs and ≈1,6 μs. For each of the three T_1 values, the mean deviation $\Delta T_{1,j}$ is calculated. The overall mean of the three $\Delta T_{1,j}$ values is:

$$\Delta T_{1m} = \frac{1}{3}\sum_{j=1}^{3}\Delta T_{1,j} \tag{B.9}$$

In other words, ΔT_{1m} denotes the mean front time error of system X, related to the reference system N, in the range T_1 = 0,8 μs … 1,6 μs.

The model function for the error of system X, corrected by the error ΔT_{1N} of the reference system N, is:

$$\Delta T_{1cal} = \Delta T_{1m} + \Delta T_{1N} \tag{B.10}$$

The individual values, errors and deviations, obtained by the calibration, are listed in Table B.5 and additionally shown in Figure B.2.

Table B.5 – Calibration result for front time T_1 and deviations

		Value		
$T_{1N,j}$	µs	0,80	1,20	1,60
$T_{1X,j}$	µs	0,73	1,17	1,61
$s_j(T_{1X,j})$	µs	0,015	0,01	0,01
$\Delta T_{1,j}$	µs	-0,07	-0,03	0,01
$\boldsymbol{\Delta T_{1m}}$	**µs**	**-0,03**		

From the maximum standard deviation of the three $T_{1X,j}$ values, the Type A standard uncertainty is calculated by:

$$u_A(T_{1X}) = \frac{1}{\sqrt{10}} \max_{j=1}^{3} s_j = \frac{0{,}015\ \mu s}{\sqrt{10}} = 0{,}004\ 74\ \mu s \tag{B.11}$$

Since T_{1X} is not mentioned directly in the model function, $u_A(T_{1X})$ is entered as a separate quantity in the uncertainty budget (Table B.6).

The maximum deviation of the three individual $T_{1X,j}$ values from their mean ΔT_{1m} gives the Type B standard uncertainty:

$$u_B(T_{1m}) = \frac{1}{\sqrt{3}} \max_{j=1}^{3} \left| \Delta T_{1,j} - \Delta T_{1m} \right| = \frac{0{,}04\ \mu s}{\sqrt{3}} = 0{,}023\,1\ \mu s \tag{B.12}$$

The values and standard uncertainties of all input quantities are entered on the right side of the model equation (B.8 with B.7). The model equation can be evaluated manually, using the equations given in Annex A, or with the aid of special software which should be validated for calculating uncertainties. The result of the evaluation is summarised in Table B.6. In the last line, the mean error ΔT_{1cal}, its combined standard uncertainty and the effective degrees of freedom are given. The large value v_{eff} = 1700 indicates normal distribution of the probable values of ΔT_{1cal}, and thus k = 2 is valid (see Annex A, Table A.1).

Table B.6 – Uncertainty budget of the front time deviation ΔT_{1cal}

Quantity	Value µs	Standard uncertainty contribution µs	Degrees of freedom	Sensitivity coefficient	Contribution to combined standard uncertainty µs
ΔT_{1N}	0,01	0,01 [1)]	50	1	0,01
ΔT_{1m}	-0,03	0,0231 [2)]	∞	1	0,023
$u_A(T_{1X})$	0,0	0,00474 [1)]	9	1	0,0047
$\boldsymbol{\Delta T_{1cal}}$	**-0,020 µs**		**1 700**		**0,0256 µs**

[1)] Normal distribution.

[2)] Rectangular distribution.

Finally, the complete result of the calibration is expressed as follows:

ΔT_{1cal} = -0,020 µs ± 0,051 µs for a coverage probability of not less than 95 % (k = 2).

In other words: The front times measured with system X in the nominal époque are too small by -0,02 μs. When system X is used for impulse voltage measurements, the corrected front time T_{1cor} is obtained by adding 0,02 μs to the measured value T_{1meas}. If no further contributions to the front time need to be considered, the expanded uncertainty of T_{1cor} is 0,051 μs (k = 2).

Additional uncertainty contributions may originate when the digital recorder of system X is used in ranges different from those during the comparison. The effect on t_{30} and t_{90} shall be estimated and a reasonable deviation of T_1 be calculated according to Equation (B.7) from which the corresponding Type B standard uncertainty is introduced in the uncertainty budget.

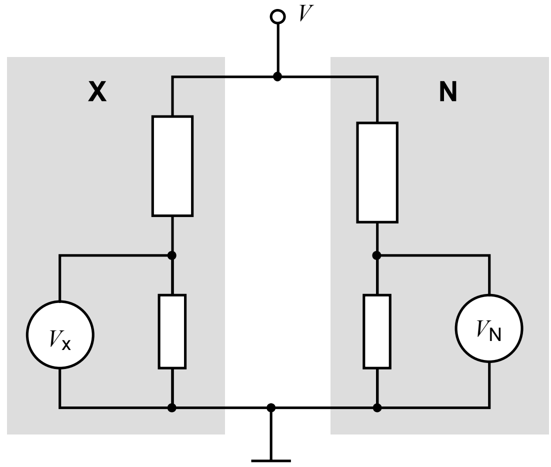


Figure B.1 – Comparison between the system under test, X, and the reference system, N

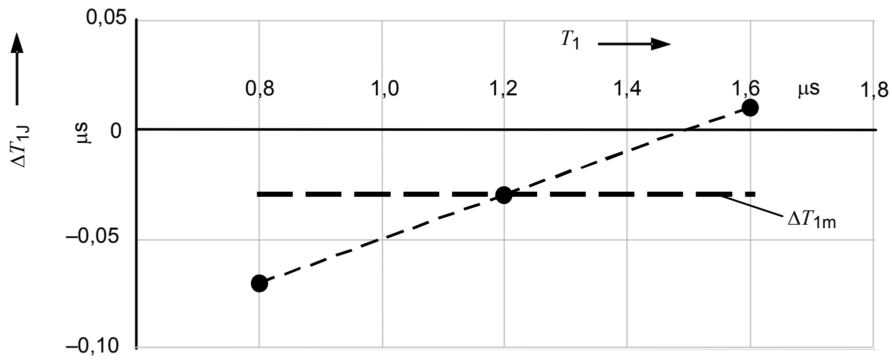


Figure B.2 – Front time deviation $\Delta T_{1,j}$ of system X, related to the reference system N, and their mean ΔT_{1m} in the range of T_1 = 0,8 μs … 1,6 μs

Annex C
(informative)

Step response measurements

C.1 General

Step response measurement is a traditional method to characterize an impulse voltage divider, an impulse oscilloscope or a digital recorder. Because there is no direct correlation between unit step response parameters and correct measurement of impulse voltages, it lost its role for the requirements of this standard, but remains important for characterizing the dynamic behaviour in connection with comparison measurements (8.4.2, 9.3.2) and especially for the development of dividers and instruments. Furthermore it is applied for performance checks of the dynamic behaviour (see 8.5.3 and 9.5.3).

For the estimation of errors in time parameter measurement by convolution (Annex D), the precise knowledge of the unit step response is necessary.

C.2 Definitions in addition to Clause 3

C.2.1
reference level (impulse measurements only),
l_R
mean value of the step response taken over the reference level epoch (see C.2.10 and Figure C.1a), i.e., over the range of $0{,}5t_{min}$ to $2t_{max}$

NOTE A measuring system may have more than one reference level, for example, it may have different scale factors for different waveforms due to the variation of the response level (see 3.5.4 and Figure C.1a).

C.2.2
origin of a step response,
O_1
instant when the response curve firstly starts a monotonic rise above the amplitude of the noise at the zero level of the (unit) step response (see Figure C.1a).

NOTE 1 In some cases the unit step response starts with an initial distortion (Figure C.2). Then the origin O_1 should be determined at the crossing of the downward extension from the point of monotonic increase of the unit step response with the zero line. The initial distortion may be characterized by a parameter T_0 (initial distortion time) which corresponds to the partial area(s) between the zero line and the unit step response up to O_1.

NOTE 2 All the time values (except T_0) are measured from the origin O_1.

C.2.3
unit step response,
$g(t)$
step response normalized such that a reference level becomes unity and the zero level remains zero (Figure C.1a).

NOTE A measuring system has a unit step response for each reference level. The origin O_1 of the step response is identical with that of the unit step response.

C.2.4
step response integral,
$T(t)$
integral from O_1 to t of one minus the unit step response $g(t)$ (see Figure C.1b):

$$T(t) = \int_{O_1}^{t} \left(1 - g(\tau)\right) d\tau \ . \qquad \text{(C.1)}$$

C.2.5
experimental response time,
$\boldsymbol{T_N}$
value of the step response integral at $2 \cdot t_{max}$:

$$T_N = T(2 \cdot t_{max}). \qquad \text{(C.2)}$$

C.2.6
partial response time,
T_α
maximum value of the step response integral for $t \leq 2 \cdot t_{max}$ (see Figure C.1b) equal to the shaded area in Figure C.1a

NOTE Usually $T_\alpha = T(t_1)$ where t_1 is the time when $g(t)$ first reaches the unit amplitude (see Figure C.1a).

C.2.7
residual response time,
$\boldsymbol{T_R(t_i)}$
experimental response time T_N minus the value of the step response integral at some specific time t_i where $t_i < 2 \cdot t_{max}$:

$$T_R(t_i) = T_N - T(t_i). \qquad \text{(C.3)}$$

C.2.8
overshoot of the unit step response,
$\boldsymbol{\beta_{rs}}$
difference between the maximum $g_{max}(t)$ and unity as a percentage of unity (Figure C.1a):

$$\beta_{rs} = 100\ \% \ (g_{max}\ (t) - 1). \qquad \text{(C.4)}$$

C.2.9
settling time,
$\boldsymbol{t_s}$
shortest time for which the residual response time $T_R(t)$ becomes and remains less than 2 % of t:

$$\left| T_N - T(t) \right| < 0{,}02t \qquad \text{(C.5)}$$

for all values of t in the epoch from O_1 to the longest time-to-half value T_{2max} of the impulse voltage to be measured (see Figure C.1b)).

C.2.10
reference level epoch (impulse voltage only)
time interval in which the reference level of the step response is determined with its lower limit being equal to 0,5 times of the lower limit of the nominal epoch ($0{,}5t_{min}$) and its upper limit being equal to 2 times the upper limit of the nominal epoch ($2t_{max}$)

C.3 Circuit for step response measurements

The circuit arrangement used for determining the step response should be described in the record of performance and should be as near as possible to the operating conditions.

Suitable circuits are shown in Figure C.3. The preferred circuit is shown in Figure C.3a where the step generator is placed at a metallic wall or at a metallic strip conductor at least 1 m wide, which serves as the earth return.

To generate the step the measuring system is supplied by either a slowly rising impulse or a direct voltage which is chopped by a relay or a gap (see Figure C.3d). The following methods of chopping have been found acceptable:

– by a relay with mercury-wetted contacts: this gives steps up to some hundreds of volts,
– by a uniform field gap in air at atmospheric pressure with a spacing up to some millimetres: this gives steps up to several kilovolts,
– by a uniform gap with a spacing up to some millimetres under increased gas pressure: this gives steps up to some tens of kilovolts.

When the step is generated using a repetitive generator, the duration of the step, and of the interval between steps shall be chosen such that no additional errors are introduced with respect to a single pulse.

C.4 Requirements for the step response of a component

The component, normally a converting device or a recording measuring instrument, is subjected to a voltage step and its output is measured. The rise time of the applied step should be less than 1/5 of the partial response time T_∞. Slight smoothing of the recorded data of the step response is recommended to reduce the influence of small oscillations and noise superimposed on the step response.

The unit step response within the selected reference level epoch should not deviate from unity by more than ±2 %. The unit step response, at the time of the corresponding voltage waveform, t_f, used for the measurement of the assigned scale factor, should not deviate from the reference level by more than ±1 % if t_f used falls outside the range of the nominal level epoch. When a full lightning impulse voltage is used in determination of the assigned scale factor, t_f is equal to $2T_1$, which is 2 times of the front time of the impulse. When a front chopped lightning impulse voltage is used, t_f is equal to $2T_c$, which is 2 times of the time to chopping of the impulse. When a switching impulse is used, t_f is equal to T_p, which is the time to peak of the impulse. When a direct voltage is used, t_f is equal to 100 ms. When and alternating voltage is used, t_f is equal to one quarter of the period of the voltage.

For step response requirements of impulse voltage reference measuring systems, see 10.2.3.

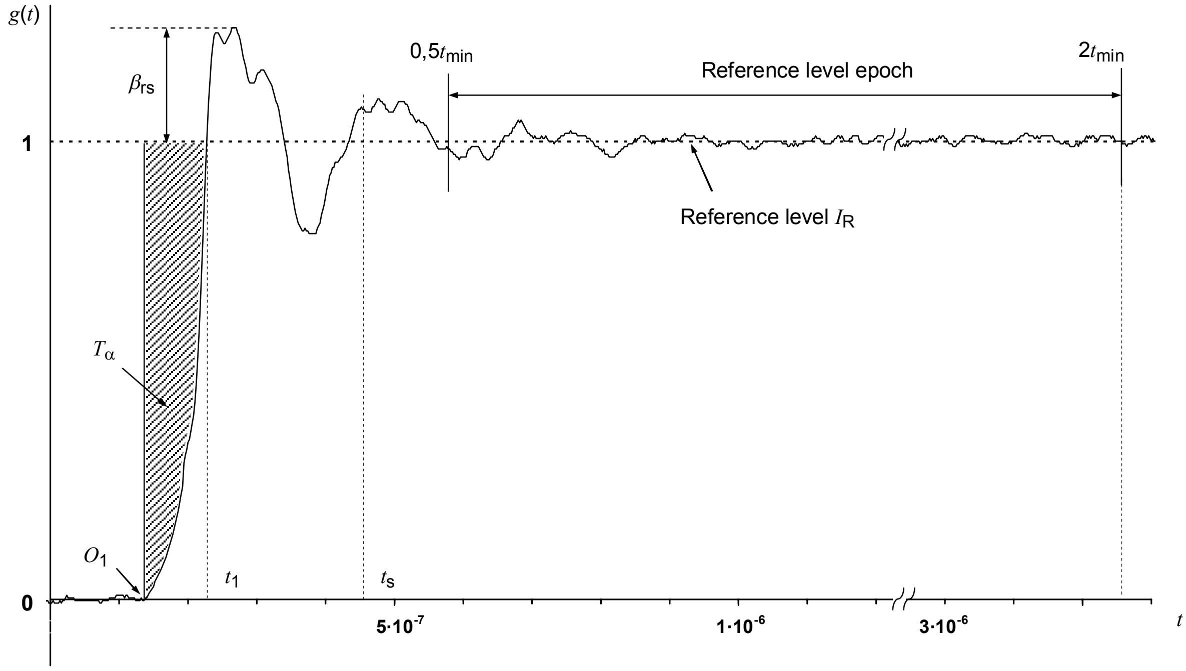


Figure C.1a – Definitions from the unit-step response $g(t)$

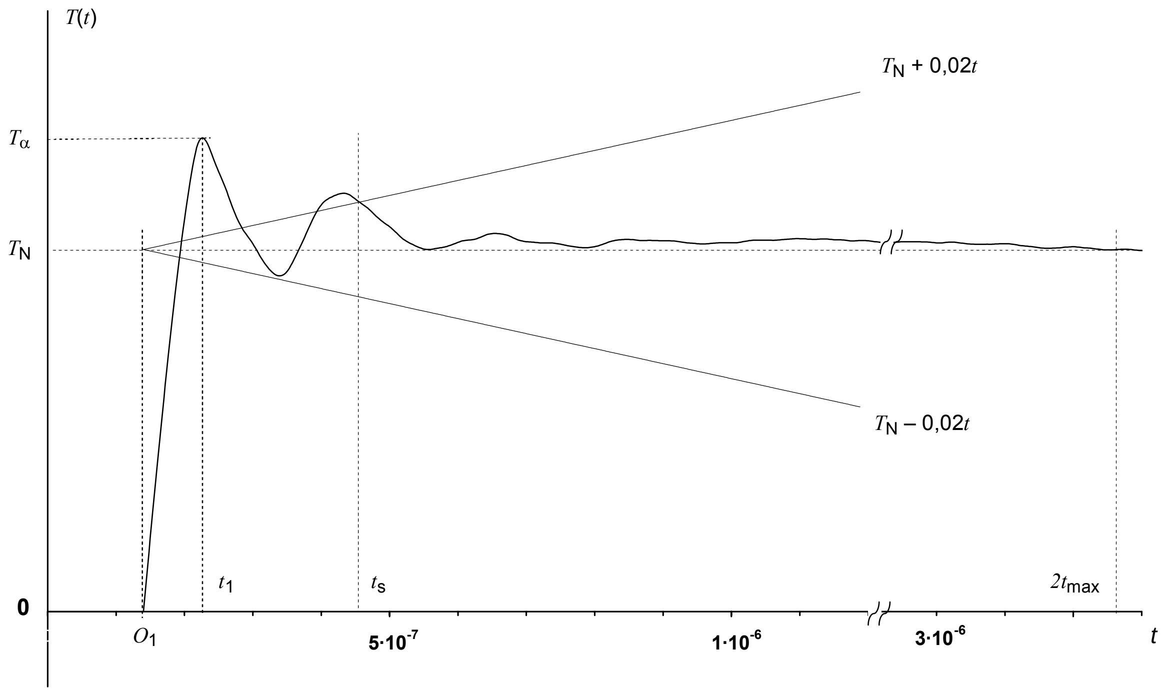


Figure C.1b – Definitions from the step-response integral $T(t)$

Figure C.1 – Definitions of response parameters

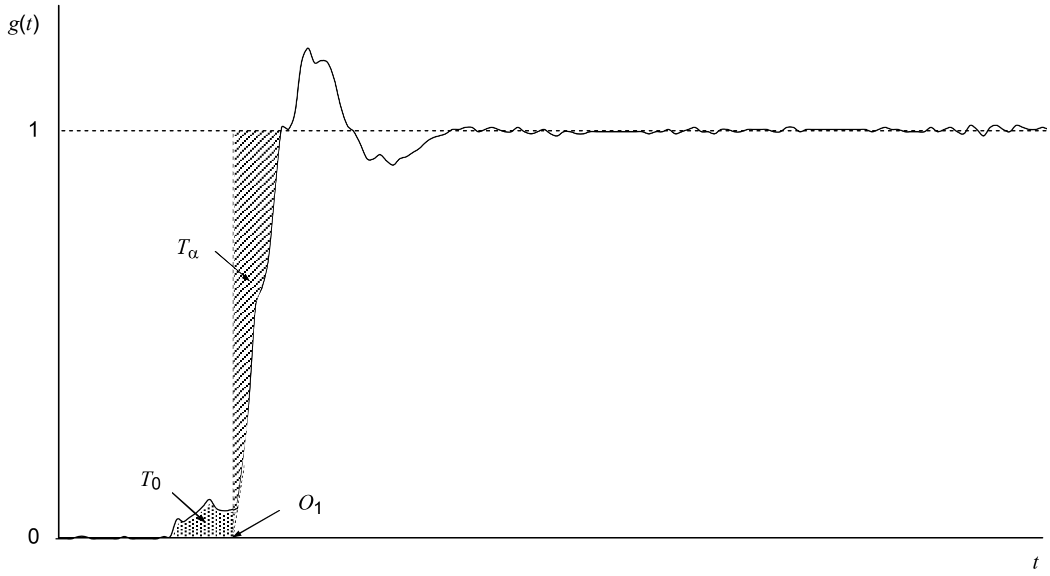


Figure C.2 – A unit-step response $g(t)$ showing an initial distortion of initial distortion time T_0

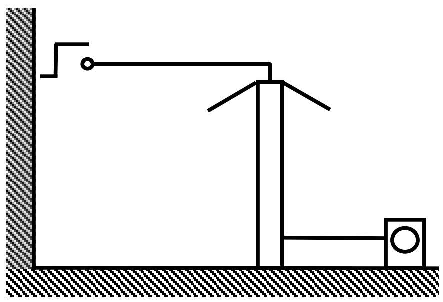


Figure C.3a – Preferred arrangement

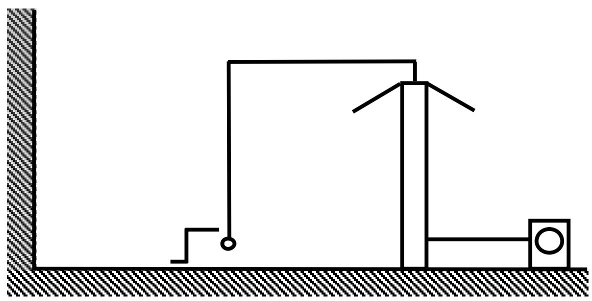


Figure C.3b – Preferred for large dividers

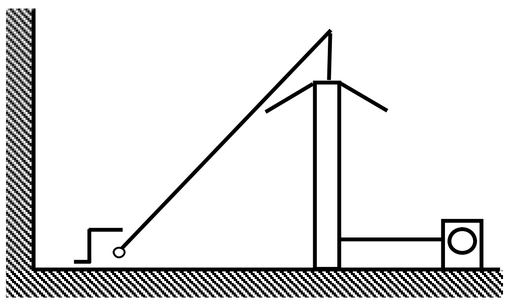


Figure C.3c – Alternative for large dividers

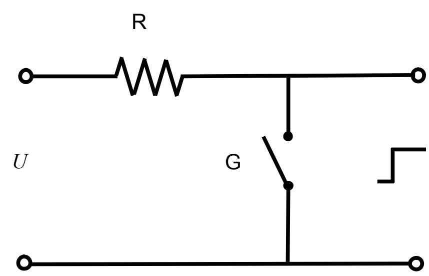


Figure C.3d – A typical step generator circuit

NOTE G is the chopping device to generate the step.

Figure C.3 – Suitable circuits for step response measurement

Annex D
(informative)

Convolution method for the determination of dynamic behaviour from step response measurements

D.1 General

The convolution method is used to evaluate the dynamic performance of an impulse voltage divider, a digital recorder, or a complete impulse voltage measuring system from their step responses (Annex C).

The convolution method uses the step response of the measuring system to calculate its output impulse waveform from the input impulse waveform. The errors of the impulse parameters of the output waveform relative to the input waveform may be used to evaluate the performance of the measuring system for a particular waveform to be measured.

The convolution method assumes that the step response of the measuring system is correctly measured and the input waveform used in the calculation is representative of the real impulse waveforms to be measured.

D.2 The convolution method

If the input impulse waveform and the unit (normalized) step response (Annex C) of an impulse measuring system are $V_{\mathrm{in}}(t)$ and $g(t)$ respectively, the output, $V_{\mathrm{out}}(t)$, may be expressed by the following convolution integral:

$$V_{\mathrm{out}}(t) = \int_0^t V_{\mathrm{in}}'(\tau) \cdot g(t-\tau) \cdot \mathrm{d}\tau \qquad \text{(D.1)}$$

where t is time and $V_{\mathrm{in}}'(t)$ is the first derivative of the input impulse voltage waveform $V_{\mathrm{in}}(t)$.

If $g(t)$ and $V_{\mathrm{in}}(t)$ are sampled with the same sampling interval and the number of samples of $g(t)$ is the same as that of $V_{\mathrm{in}}(t)$, the continuous convolution integral (D.1) reduces to the causal form of the discrete convolution sum:

$$V_{\mathrm{out}}(i) = \sum_{k=0}^{i} V_{\mathrm{in}}'(k) \cdot g(i-k) \cdot \Delta t \quad i = 0, 1, 2, \ldots, n-1 \qquad \text{(D.2)}$$

where:

$V_{\mathrm{out}}(i)$ is the discrete output array;

$V'_{\mathrm{in}}(i)$ is the first derivative of input array;

$g(i)$ is the unit step-response array;

n is the number of samples of the input array; and

Δt is the sampling interval of the input and output arrays, and the step-response array.

D.3 Procedure for performing the convolution calculation

This procedure is based on the discrete convolution sum described by equation (D.2). It is used for computer-aided calculation using digital impulse waveforms. The procedure is used to estimate the errors of the impulse parameters of the output relative to the input waveforms of an impulse measuring system. The procedure given here describes the major steps of calculation. These steps are:

a) Obtain the input impulse-waveform array $V_{in}(i)$ for $i = 0, 1, 2, \ldots, n-1$, and calculate its impulse parameters.

b) The sampling rate of the input impulse waveform should be identical to that of the unit step response, with the number of its samples equal to that of the unit step response (see step c). The input waveform should be a smooth waveform with the highest frequency of the noise having been reduced well below the Nyquist frequency (half of the sampling frequency of the impulse array). A smooth input waveform array and its impulse parameters may be derived either:

   1) from an analytical expression of the impulse, e.g., a superposition of two ideal exponential functions. The impulse parameters of this waveform may either be obtained from the analytical expression or from the impulse calculation software of the impulse measuring system being examined.

   2) or from a recorded real waveform, smoothed by a precision low-pass digital filter or a piecewise cubic spline fitting algorithm. The impulse parameters of this waveform may be obtained from the impulse calculation software of the impulse measuring system being examined.

c) Obtain the first derivative $V'_{in}(i)$ for $i = 0, 1, 2, \ldots, n-1$, of the input impulse waveform $V_{in}(i)$ by numerical derivation.

d) Obtain the unit step response array $g(i)$ for $i = 1, 2, \ldots, m-1$ and $m = n+j$, where j is the number of data points before the origin of the recorded step response O_1.

   1) Obtain the unit step response by normalizing the measured step response (Annex C). To obtain a low-noise unit step response for convolution purposes, averaging several step-response records may be used. The smoothness of the unit step response array $g(\mathrm{i})$ is less critical if equation (D.2) is used for the convolution calculation and the impulse array $V_{in}(i)$ is already smooth.

   2) Obtain the zero level, l_0, of the step response by averaging the samples of the recorded step-response array $s(i)$ before the starting edge of the step.

   3) Obtain the reference level, l_R, of the step response by averaging the samples of the recorded step-response array $s(i)$ within a time range including the shortest front time for which the measuring system is to be used, and up to the time reflecting the frequency at which the scale factor of the converting device has been determined.

   4) Normalize the step-response array $s(i)$ into a temporary unit-step-response array, $g_0(i)$, by using the following formula:

$$g_0(i) = \frac{s(i) - l_0}{l_R - l_0} \qquad \text{(D.3)}$$

   5) Find the noise amplitude at the zero level by finding the standard deviation, d_0, of the samples of the $g_0(i)$ array before the start of the step. Searching backwards from the end of $g_0(i)$, find the sample with its value being higher than three times of the standard deviation d_0. The time of this sample is assigned as the origin, O_1, of $g_0(i)$. Assign the index of this sample to j.

   6) Construct the unit step response $g(t)$ from the origin by removing the samples of $g_0(i)$ before the origin, i.e.:

$$g(i-j) = g_0(i), \quad i = j, \ldots, m+j-1 \qquad \text{(D.4)}$$

NOTE Recorded $g_0(i)$ has $m+j$ points. Unit step response $g(i-j)$ has $n=m$ points after removing j points before the origin O_1.

e) Obtain the output array and its impulse parameters array:

1) Obtain the output impulse waveform array $V_{out}(i)$ by calculation using equation (D.2) either in the time domain or in the frequency domain.
2) Calculate the impulse parameters of $V_{out}(i)$ using the impulse calculation software of the impulse measuring system.
3) Calculate the errors of $V_{out}(i)$ as the difference between the impulse parameters of $V_{out}(i)$ and $V_{in}(i)$.

D.4 Uncertainty contributions

In principle, the errors calculated by the convolution may be used for correcting the parameters calculated. Such correction does however require à priori knowledge of the wave-shape, i.e. unless the impulse is of known regular shape, the correction is not reliable. The errors and their scatter for different wave-shapes, can be used as an uncertainty contribution to the combined uncertainty of measurement of the parameter concerned. Uncertainty calculation should be performed in accordance with the ISO/IEC Guide 98-3, see also Annex A, with examples given in Annex B.

D.5 Discussion of the calculated errors of impulse parameters

D.5.1 Error in the peak amplitude

The unit level of the unit step response is usually not constant. Therefore, the calculated error of the peak amplitude is often significant in comparison with the numerical error of the convolution calculation, although it may be small in comparison with the required measurement uncertainty of the peak amplitude. The calculated relative error of the peak amplitude should be equal to the relative difference between unity and the value of $g(i)$ at a time approximately equal to 2 times the front time T_1 of the input impulse $V_{in}(i)$. The calculated error in the peak amplitude can be compared to the unit step response to verify if the convolution calculation has been performed correctly.

D.5.2 Error in the front time

The convolution calculation can reveal a change in the wave shape of the impulse caused by the performance of the measuring system, and therefore the magnitude of the error of the front time, which cannot be revealed by the step response itself. As the consequence of a slower step response, the front time of the output impulse becomes larger. However, the front time is also influenced by the overshoot/undershoot of the step response. Depending on the time-positions of the overshoot and undershoot on the step response, the front part of the impulse waveform may be changed into different shapes, leading to either an increased or decreased front-time value.

D.5.3 Error in the time to half-value

The time to half-value is mainly affected by the difference between the $g(i)$ value at a time approximately equal to 2 times the front time T_1 and the $g(i)$ value at the time equal to T_2 of the impulse being evaluated. The convolution calculation can be used to estimate the magnitude of the error of T_2, which cannot be directly estimated from the step response itself.

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1 To be published.

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For the purpose of deciding whether a particular requirement of this standard is complied with, the final value, observed or calculated, expressing the result of a test or analysis, shall be rounded off in accordance with IS 2 : 1960 'Rules for rounding off numerical values (*revised*)'. The number of significant places retained in the rounded off value should be the same as that of the specified value in this standard.

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