Chapter 19

Traceable measurements in high voltage tests

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19.1 Introduction

Traceability is defined as an unbroken chain of comparisons (calibrations), each having a stated uncertainty, which relates the result of a measurement or the value of a standard to stated references. Wherever practical the maintained electrical standards are taken as such references.

A chain of measurements can be extended from any convenient reference point in such a chain, providing the route to a primary standard of measurement can be traced. An accredited calibration laboratory provides a widely accepted point of reference in the chain of traceability. [3]

Although in many countries traceability through accredited calibration laboratories for a range of measurements (mass, temperature, low voltage) is readily available, a similar service for high voltage measurements is not so common. The concept of the approved measuring system introduced in IEC Publication 60060–2: 1994 [1] helps to redress that deficiency.

The concept regards the complete measuring system as an entity in the traceability chain, and it includes the voltage divider (or other converting device), lead from the test object, lead damping resistor, low voltage transmission system, attenuator, recording instrument and earthing cables.

The designation of Approved Measuring System is applied by the user to a measuring system which is shown to comply with requirements of an Initial Performance Test (I). The designation cannot be presumed to apply indefinitely, and the user is required to perform regular performance checks, and to repeat the performance test at less frequent intervals. The results of all of these calibrations and checks are recorded in a record of performance, maintained by the user for each measuring system. This history of calibrations and checks is an important contribution to the evidence of traceability.

A statement of the estimated uncertainty for every measurement in a chain of calibrations is an essential requirement for traceability. High voltage tests do not usually involve a sufficient number of observations for an estimation of overall uncertainty to be made by purely statistical methods, and a considerable degree of common sense reasoning must be applied when estimating individual contributions to an uncertainty budget. The combination of individual uncertainty contributions due to various influencing factors, to give an estimate for the overall uncertainty of measurement at a given level of confidence, can be made by a simple procedure described in IEC Publication 60060–2, Amendment 1:1996 [2] [11].

19.2 Direct voltage

The measurement of all electrical quantities is based on national standards of direct voltage and resistance traceable to the standards of other countries by comparisons performed periodically at the Bureaux Internationale Poids et Measures, BIPM. These standards are compared to within one part in 10^8 but the uncertainty in absolute value is estimated to be about one part in 10^6. They are currently evolving towards different, but more stable, devices such as those based on Josephson and quantum Hall effects.

The calibrations of DC voltmeters up to 1 kV are directly traceable to the primary voltage standards through self-calibrated voltage dividers with uncertainties of 10^{-5}.

Intercomparison measurements by several national laboratories [4] have resulted in voltage dividers for a few hundred kilovolts with uncertainties of 10^{-5} being available in a number of countries. Calibrations of reference dividers, with an uncertainty of 1%, can be achieved with existing techniques.

19.3 Alternating voltage

Alternating voltages up to a few hundred volts, at power frequency, can be measured by comparison with direct voltages through AC/DC transfer devices, with uncertainties of 10^{-4}. Traceable calibration at higher voltages is a well established procedure using voltage transformers or voltage dividers.

Intercomparison measurements by several National Standards Laboratories in Europe, on a voltage transformer and on a compressed gas capacitor, have resulted in National Reference Measuring Systems being available up to 100 kV with overall uncertainties of 10^{-5} [5, 6].

Industrial testing laboratories regularly perform calibrations of voltage transformers with uncertainties in the range of 10^{-4}, for tariff metering equipment. Voltage transformers calibrated to an uncertainty of 10^{-3} are readily available, easily transportable and influenced very little by ambient conditions. They provide the best working reference standard for an accredited calibration laboratory, up to several hundred kilovolts. Compressed gas capacitors, available for voltages up to 1 MV, are not influenced much by ambient conditions. The capacitance is usually independent of voltage, frequency and small temperature changes to within 1 part in 10^3 and they can be used in a testing laboratory after a low voltage check of capacitance. With special precautions during transport they have been used very successfully as transportable working references [7]. As with DC, low voltage measurement in AC systems is by readily available digital voltmeters of sufficient accuracy. An overall uncertainty of 1% specified for reference systems can be achieved by existing procedures.

19.4 Impulse voltage

Traceability to primary standards of voltage for impulse measurements is more difficult to achieve. Only a few national standards laboratories are engaged in impulse measurements. Calibration of impulse recorders is not yet readily available for uncertainties better than 1% for voltage. Although the sampling frequency can be measured with traceability to the unit of time, the evaluation of the time parameters of an impulse requires the determination of the crossing of voltage levels at specified times, e.g. at 0.3 and 0.9 of the peak value. The uncertainty of the time parameters for full lightning impulses is estimated to be about 1%.

The concept of international traceability for impulse voltage measurements is participation by national standards and accredited calibration laboratories in intercomparison tests, with the achievement of small deviations between the results from all laboratories.

Several intercomparisons of impulse measuring systems by national and industrial laboratories in Europe and North America, with full and front-chopped lightning impulses in the range 100 kV to 200 kV, have shown that uncertainties of less than one-third of the limits for voltage and time errors required by the International Standard [1] are achievable [8, 9]. Many laboratories agreed to within 0.2% in the measurement of the peak value of full lightning impulses. As more experience is gained it is expected that accredited calibration laboratories should achieve uncertainty values, in calibrations by comparative measurement techniques with full and front-chopped lightning impulses, of less than 0.5%.

The evaluation of the front time and other time parameters can be affected by oscillations superimposed on the impulse shape. Several smoothing techniques, among them digital filtering, are known to work but they must be applied carefully.

A measuring system for impulse voltages does not necessarily have a unique value of scale factor. Calibration over the complete range of impulse shapes to be measured is necessary and a correct measurement of the unit step response is a part of the traceability procedure.

The scale factor of a digital recorder must be measured for the relevant impulse shapes, and for all its input ranges deviations of several percent can occur.

19.5 Linearity test

The voltage rating of many systems is likely to be much higher than the voltage at which a comparative measurement with a reference system can be made to provide a traceable calibration of scale factor. A measurement of scale factor may be at a voltage as low as 20% of the maximum voltage for which the system is to be approved and used. Additional tests must then be made to prove that the scale factor is linear up to the required value of voltage. There is no single test that will meet all situations. One or more of a number of tests must be performed to provide the necessary evidence of linearity.

Where another system of a higher voltage rating, which has already been qualified as an approved measuring system, is available, then the linearity test may be made by a comparative measurement technique against the approved system. The scale factor, however, must be determined from the comparative test with the reference system at the lower voltage.

A voltage divider consisting of several sections in series can sometimes be checked for linearity by testing separately each of the sections up to its proportion of the maximum voltage for which the complete divider is to be approved. Then the complete divider must be tested to check that no partial discharges occur at the highest voltage needed for approval. The linearity of a converting device may be affected by corona above a certain voltage, resulting in a change of scale factor. The detection of DC and AC corona with commercially available instruments is a relatively simple test. However, for impulses, it may be necessary to record and compare the impulse waveshape at various voltages.

The relation between the charging voltage of an impulse generator and its output has been shown to be constant within 1% and can therefore be used to demonstrate linearity. Tests for linearity may be performed against an IEC standard measuring device, a rod gap for DC and an irradiated sphere gap for impulse and AC. It is necessary to show that each measured value is within 2% of the corresponding IEC sparkover voltage.

Recently developed field sensors seem likely to provide the most useful technique to prove the linearity of a converting device.

19.6 Uncertainty of measurement

The uncertainty in a measurement [10] is an important factor in any statement about its traceability. All measuring systems are influenced to some degree by factors not necessarily directly related to the quantity being measured. Corrections can sometimes be made for parameters (e.g. ambient temperature, proximity effect) where these effects are constant and are known, and where screening of the system from them is not possible, but some uncontrollable influences remain.

If a measurement is repeated several times under apparently constant conditions there will be a spread in the observed results. If the tests can be repeated many times it is usually found that most of the results fall close to one central value and that the distribution of the results is Gaussian. The central value tends to become constant as the number of measurements increases and can be regarded as the mean value of the distribution.

Most high voltage tests are characterised by only a single or small number of measurements of voltage. A single measurement has a chance of taking any value in the expected distribution, and the difference between this single measurement and the mean value of the distribution gives rise to a random component of uncertainty. In most measurements, the overall uncertainty will result from a combination of systematic and random uncertainty contributions.

Arithmetic summation of the contributions in an uncertainty budget is likely to give an unrealistic and pessimistic value. A more realistic method of combining uncertainty contributions is generally given by using a root sum of squares method, which makes allowance for the probability that not all contributions will act simultaneously in the same direction. A statement of uncertainty should include the method of combination of the contributions and the level of confidence (e.g. 95% confidence level) in the given value of overall uncertainty.

Examples of systematic uncertainty are:

- calibration uncertainties
- errors in graduation of an instrument scale
- use of an instrument under constant conditions, but different from those of calibration.

Examples of random uncertainty are:

- measurement of electrode separation in an airgap
- proximity effect

- voltage shape
- setting a pointer to a fiducial mark on a scale
- interpolation between marked points on an analogue scale
- digitising error
- interference
- fluctuation in any influence parameter, e.g. air temperature, humidity.

In the example, 1072 ± 16 kV, the value of 16 kV is the estimate of overall uncertainty, obtained by the method of root sum of squares, for an estimated confidence level of 95%.

19.7 Definitions related to accreditation

Accreditation
Formal recognition that a laboratory is competent to perform specific calibrations or tests.

Accredited laboratory
A laboratory that meets the general requirement for quality control specified by an accrediting body and the special requirements for high voltage and impulse current measuring systems in the relevant standards.

Accrediting body
The official national authority responsible for the granting, renewal or termination of accreditation in respect of calibration or testing laboratories. It negotiates agreements on mutual recognition with other national schemes to obtain international acceptance of the competence of accredited laboratories. Many countries have completely separate organisations for accrediting calibration laboratories and for accrediting testing laboratories.

Approved measuring system
A measuring system which is shown in its record of performance to comply continuously with the requirements for accuracy and performance in the relevant standard.

Calibration
Specific type of measurement on measurement standards, measuring instruments and measuring systems to establish the relationship between the indicated and known values of a quantity. Calibration may be performed in a standards laboratory or in a testing laboratory.

Measuring system
A complete set of devices suitable for performing a high voltage or impulse current measurement.

Quality system
The organisational structure, responsibilities, procedures, processes and resources for implementing quality management, formalised in a maintained quality manual.

Record of performance of a measuring system
A working document, established by the user. It contains the complete history of the system and the latest measured values of the scale factor.

Reference measuring system
A measuring system having a calibration traceable to a national standard of measurement and used solely for the calibration or approval of other measuring systems by simultaneous comparative measurement.

Reference standard of measurement
A device of the highest meteorological quality at a given location, from which measurements at that location are derived.

Test
All types of objective measurement except calibration, performed in any location.

Traceability of measurement
The property of a result of a measurement by which the measurement can be related to the relevant national or international standard of measurement by an uninterrupted chain of comparisons.

19.8 Definitions related to uncertainty

Arithmetic summation of uncertainties
The most pessimistic method of combining uncertainty contributions, namely

$$U_{\mathrm{TOTAL}} = |U_1| + |U_2| \ldots + |U_n|$$

where $|U_1|$ to $|U_n|$ are the moduli (i.e. the magnitudes are all taken as positive) of the contributions.

Confidence level
The probability that the true value (q.v.) will lie within a defined range of values. The rules governing its evaluation depend on the assumed or measured distribution of values.

Control quantity
One of the quantities whose magnitude is specified as a reference condition for the test.

Conventional true value (of a quantity)
A value approximating to the true value of a quantity such that for the purpose for which that value is used, the difference between the two values can be neglected.

Correction
The value which, when added algebraically to an indicated or measured value, corrects for a known or assumed error.

Distribution
The frequency of occurrence of different magnitudes of value throughout a measured, or assumed, range of values.

Error of measurement
The result of a measurement minus the true value of the measured quantity. A term which cannot be quantified since the true value lies somewhere unknown within the range of the uncertainty.

Error of measuring instrument
The difference between the value indicated by an instrument and the most probable (or the conventionally true) value of the measured quantity. Such an error is correctable by addition of a correction (equal, but opposite in sign, to the error).

Experimental standard deviation (s)
From a limited sample of measured values of a quantity, an estimate of the standard deviation in terms of the whole population is given by

$$s = \left[\frac{1}{n-1} \sum_{m=1}^{n} (x_m - x)^2 \right]^{1/2}$$

where n is the number of measurements, x_m are the measured values for $m = 1$ to n and x is the mean of the measured values.

Gaussian distribution
A distribution of a form shown graphically in Figure 19.1*b*, alternatively known as a normal distribution.

Indicated value

1. The indicated or recorded value of a measuring instrument.

2. The nominal or stated value of a material measure.
3. The set or nominal value of a supply device.

Limit of error and uncertainty
The sum of uncorrected error and uncertainty to give a maximum limit to the error of a measurement or a test. See also Error of measurement and Permissible limit of error and uncertainty.

Mean value
The average value of a set of readings or measurements of the same quantity. Denoted by a bar over the variable, e.g. $\bar{x}$.

Nominal value
The manufacturer's specified value of a component.

Permissible limit of error and uncertainty
A maximum value of the sum of uncorrected error and uncertainty in the measured value of a quantity permitted by contract, regulation or legislation. The permissible limit is obtained by the arithmetic summation of uncorrected error and uncertainty, the latter being the value at a confidence level of not less than 95%. See also Limit of error and uncertainty.

Random error
Component of the error of measurement which, in the course of a number of measurements of the same measurand under the same measurement conditions, varies randomly with expectation zero.

Rectangular distribution
A particular form of distribution shown graphically in Figure 19.1*a*. It is characterised by the equal probability assigned to any value in its range.

Repeatability of measurements
The closeness of the agreement between the results of successive measurements of the same measurand carried out subject to all the following conditions:

- the same method of measurement
- the same observer
- the same measuring instrument
- the same location
- the same conditions of use
- repetition over a short period of time.

Note: Repeatability may be expressed quantitatively in terms of the dispersion of the results.

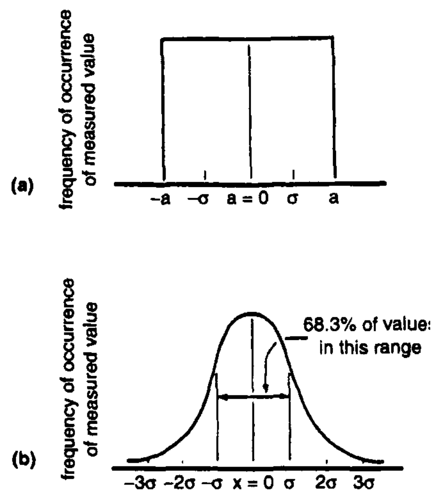

Figure 19.1 **(a)** *Value as difference from mean ($\bar{a}$) – rectangular distribution;* **(b)** *value as difference from mean ($\bar{x}$) – Gaussian distribution*

Reproducibility

The closeness of the agreement between the results of measurements of the same measurand, where the individual measurements are carried out, changing conditions such as:

- method of measurement
- observer
- measuring instrument
- location
- conditions of use
- time.

Notes: Reproducibility may be expressed in terms of the dispersion of the results. A valid statement of reproducibility requires specification of the conditions changed.

Root sum of squares (RSS) of uncertainties

The most optimistic method of combining uncertainty contributions, namely

$$U_{\mathrm{TOTAL}} = (U_1^2 + U_2^2 \ldots + U_n^2)^{1/2}$$

where U_1 to U_n are the magnitudes of the contributions.

Standard deviation, σ or s

A measure of the dispersion of a set of values. σ is generally associated with the population standard deviation. The experimental standard deviation (s) is usually used as a measure of a finite sample of values.

Systematic error
A component of the error of a measurement which, in the course of a number of measurements of the same measurand under the same measurement conditions, remains constant.

True value (of a quantity)
The value which characterises a quantity perfectly defined, in the conditions which exist when that quantity is considered.

Note: The true value is an ideal concept, and in general, cannot be known exactly.

Uncertainty of measurement
The result of the evaluation aimed at characterising the range within which the true value of a measurand is estimated to lie, generally with a given likelihood.

Note: Uncertainty of measurement comprises, in general, many components. Some of these components may be estimated on the basis of the statistical distribution of the results of series of measurements and can be characterised by experimental deviations. Estimates of other components can only be based on experience or other information.

19.9 References

1 IEC 60060-2: 1994 'High voltage testing techniques. Part 2. Measuring systems'
2 IEC 60060-2: 1994, Amendment 1:1996
3 ISO/IEC 17025: 1999 'General requirements for the competence of testing and calibration laboratories'
4 DEACON, T.A.: 'Intercomparison measurement of the ratios of a 100 kV DC voltage divider'. BCR Report EUR 10178 EN, Brussels, 1985
5 BRAUN, A. and RICHTER, H.: 'Intercomparison of the calibration of a voltage transformer'. BCR Report EUR 10193 EN, Brussels, 1985
6 SCHON, K. and LATZEL, H.G.: 'Intercomparison measurements capacitance and loss factor at high voltage'. BCR Report EUR 11453 EN, Brussels, 1988
7 RUNGIS, J. and BROWN, D.E.: 'Mobile HV calibration unit', *Aust. Phys.*, 1979, **16**, pp. 160–161
8 McCOMB, T.R., *et al.*: 'International comparison of HV impulse measuring systems', *IEEE Trans. Power Deliv.*, 1988, **PWRD-4**, pp. 906–915
9 SCHON, K. and SCHULTE R.: 'Intercomparison of HV impulse measurements.' BCR Report, Brussels, 1991
10 'Uncertainties of measurement for NAMAS Electrical Product Testing Laboratories'. NIS20
11 S. HARKNESS, R.C. HUGHES, T.R. MCCOMB, G. ZINGALES. Using IEC Publication 60-2 and Annex H to implement internal calibration in a high voltage test laboratory. ERA Conference, Milan, 1996