
Guide on

High-voltage testing techniques

Part 4. Application guide for measuring devices

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Part 4. Application guide for measuring devices]

Guide pour les techniques des essais à haute tension
Partie 4. Guide d'application des dispositifs de mesure

Anleitung zu Hochspannungsprüfmethoden
Teil 4. Anleitung zur Anwendung der Meßgeräte

National foreword

This British Standard has been prepared under the direction of the Power Electrical Engineering Standards Committee. With Parts 1, 2 and 3 it is a revision of BS 923 : 1972, which is therefore withdrawn, and the four Parts are identical with Parts of IEC Publication 60 'High-voltage test techniques' published by the International Electrotechnical Commission (IEC). This Part is identical with IEC Publication 60-4 : 1977 'Application guide for measuring devices'.

Terminology and conventions. The text of the international standard has been approved as suitable for publication, without deviation, as a British Standard. Some terminology and certain conventions are not identical with those used in British Standards.

Where page numbers are quoted in the text, they refer to IEC page numbers, which are shown in square brackets at the foot of each page.

International standard	Corresponding British Standard
IEC 60	BS 923 Guide on high-voltage testing techniques
IEC 60-2 : 1973	Part 2 : 1980 Test procedures (Identical)
IEC 60-3 : 1976	Part 3 : 1980 Measuring devices (Identical)
IEC 52 : 1960	BS 358 : 1960 Method for the measurement of voltage with sphere-gaps (one sphere earthed) (Technically equivalent)

NOTE. At present there is no corresponding British Standard to IEC 186 : 1969.

The technical committee has reviewed the provisions of IEC 186 to which reference is made in clause 12, and has decided that they are acceptable for use in conjunction with this standard.

A related British Standard to IEC 186 : 1969 is BS 3941 : 1975 'Voltage transformers'.

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British Standard Guide on

High-voltage testing techniques

Part 4. Application guide for measuring devices

SECTION ONE – GENERAL

1. Scope

This application guide is applicable to:

- measurement of direct voltages;
- measurement of alternating voltages;
- measurement of impulse voltages;
- measurement of impulse currents;
- measuring errors.

2. Object

The object of this application guide is to provide information on:

- measuring devices for direct voltages;
- measuring devices for alternating voltages;
- measuring devices for impulse voltages;
- measuring devices for impulse currents;
- statistical evaluation of measuring errors.

In general, use of the devices and of the measuring and calibration procedures described herein will satisfy the requirements of accuracy specified in IEC Publication 60-3, High-voltage Test Techniques, part 3: Measuring Devices. Their use is not mandatory: others may be used if they are shown to have equal accuracy. Voltage measurements with sphere-gaps are dealt with in IEC Publication 52, Recommendations for Voltage Measurement by Means of Sphere-gaps (One Sphere Earthed).

SECTION TWO – MEASUREMENT OF DIRECT VOLTAGES

3. General

Systems for measuring direct voltages generally consist of a measuring instrument and a high impedance across which almost the entire test voltage will appear. The value of the impedance is made high to minimize the power consumption of the measuring system. Some of the more commonly used systems for measuring the steady-state and ripple values are described below.

4. Systems for measuring the steady-state value of direct voltages

a) *Instrument used with series resistor*

A direct current measuring instrument is connected in series with a stable high ohmic value resistor.

b) *Instrument used with voltage divider*

A voltmeter is connected across the low voltage arm of a resistance voltage divider. The resistance of the voltmeter must be taken into account when determining the ratio of the divider.

Note. – Depending on the type of instrument used, these methods will determine the arithmetic mean, the r.m.s. or the peak value of the voltage.

c) *Electrostatic voltmeter*

An electrostatic voltmeter has two electrodes which are connected to the points between which the high voltage is to be measured. The electrostatic field between the electrodes generates an attracting force which is proportional to the r.m.s. value of the voltage. By measurement of this force, an indication of the r.m.s. value of the high voltage can be derived. This measuring principle can be used over the range of frequencies from zero up to several megahertz. If the measuring system is not shielded, special attention should be given to errors caused by stray fields and space charges.

d) *Generating voltmeter*

A generating voltmeter is a capacitive device the input terminals of which are connected to the points between which the voltage is to be measured. It is essentially a variable capacitor, the capacitance being cyclically changed between two fixed values. A measuring instrument together with a suitable switching or rectifying device measures the change of charge which, in general, is proportional to the mean value of the direct voltage. By a suitable choice of frequency of the capacitance variation and its phase angle relative to the voltage to be measured, the peak value or any intermediate value can be determined.

5. Systems for measuring ripple voltage

a) *Oscilloscope used with voltage divider*

An oscilloscope is connected to the low voltage arm of a voltage divider having a suitable frequency response. It should be noted that the capacitance of the cable between the divider and the instrument can modify the frequency response.

b) *Instrument used with filter*

Such a device consists in general of an instrument connected to the circuit in such a way that the d.c. component is filtered out. A typical arrangement consists of a high voltage capacitor in series with a resistor across which a voltage measuring instrument is connected.

c) *Instrument measuring the rectified current through a capacitor*

A capacitor in series with a full-wave rectifier is connected to the points between which the voltage is to be measured. The ripple amplitude U_r is related to the rectified mean current I_r flowing through the capacitor by:

$$U_r = \frac{I_r}{4 C f}$$

where:

C = capacitance of the capacitor

f = fundamental frequency of the ripple

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

The method is of limited application. If the ripple has more than one peak during each half-cycle, then the accuracy depends upon the type of rectifier which is used.

6. Determination of voltage ratios and scale factors

a) *Instrument used with series resistor*

The resistance of the series resistor is generally determined by a low voltage bridge measurement using direct voltage. From this value and the characteristics of the instrument, the scale factor is deduced.

The scale factor can also be determined by comparison during parallel operation with an approved direct voltage measuring system.

The voltage and temperature stability of the series resistor at high voltage can be verified by subjecting individual components of the resistor to suitable tests over the range of voltages and temperatures at which they will operate.

b) *Instrument used with voltage divider*

Methods for determining the ratio of voltage dividers are discussed in Clause 17.

c) *Electrostatic voltmeter and generating voltmeter*

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

Note. – During reactions between proton or deuteron beams with different light nucleus elements, precisely known resonant energies exist for which the cross-section for a reaction is a maximum. This effect can be used as a very accurate absolute calibration method for high d.c. voltage measuring systems.

7. Determination of the amplitude-frequency response of a measuring system

To determine the amplitude-frequency response of a measuring system, a sinusoidal voltage is applied between its input terminals. The ratio of the output to the input amplitudes is recorded as a function of frequency. The range of frequencies should extend from a low value to at least the highest of importance present in the voltage to be measured. The measurements are usually made at a low value of input voltage.

8. Possible sources of error and precautions

When using direct voltage measuring systems of very high resistance, care must be exercised to avoid errors due to corona effects, or to leakage currents across insulating surfaces which may be contaminated by pollution or condensed moisture. Suitably dimensioned high voltage electrodes, guard circuits and surface treatment minimize such errors and thus the requirements for current level can be reduced.

Errors can also be caused by resistors which have significant voltage or temperature coefficients and by instruments which are subject to drift.

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

Overstressing of components in measuring equipment upon flashover of a test object or measuring errors due to partial discharges can occur in a measuring system having a high frequency response appreciably in excess of its response in the low frequency range. These phenomena are usually associated with the presence of stray inductance.

SECTION THREE – MEASUREMENT OF ALTERNATING VOLTAGES

9. General

Systems for measuring alternating voltages generally consist of a measuring instrument and a voltage transformer, voltage divider, or a high impedance across which almost the entire test voltage will appear. The devices usually have high impedance to keep the loading of the test circuit within acceptable limits. Some of the more commonly used systems for measuring high alternating voltages and the amplitudes of harmonics are described.

10. Systems for measuring the amplitude of alternating voltages

The following systems will in most cases measure the peak or the r.m.s. value of an alternating voltage or the mean value of a rectified alternating voltage according to the type of instrument and arrangement used. Measurement of the rectified capacitance current (method *c*)) will determine the peak-to-peak amplitude, and the electrostatic voltmeter (method *d*)) measures the r.m.s. value.

a) Instrument used with voltage transformer

A voltmeter is connected across the low voltage winding of a voltage transformer of either the inductive or capacitive type. In general, the choice of the instrument is not restricted by its input impedance.

b) Instrument used with voltage divider

A voltmeter or an oscilloscope is connected across the low voltage arm of the divider through a measuring cable. In general, the input impedance of the low voltage measuring circuit including the measuring cable affects the divider ratio. In most cases, a capacitive voltage divider together with a low voltage circuit measuring the peak value of the high voltage is used.

c) Capacitor used with a rectifying device

A capacitor in series with a full-wave rectifier is connected to the points between which the voltage is to be measured. The peak value of the voltage U_p is related to the rectified mean current I_r flowing through the capacitor by

$$U_p = \frac{I_r}{4 C f}$$

where:

C = capacitance of the capacitor

f = frequency of the alternating voltage

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

The method is of limited application. If the waveform has more than one peak during each half-cycle, then the accuracy depends upon the type of rectifier which is used.

d) Electrostatic voltmeter

This device is described in Item *c)* of Clause 4 for use with direct voltages. It can also be used for measuring the r.m.s. value of alternating voltages in a large range of frequencies up to several megahertz.

e) Generating voltmeter

A generating voltmeter is described in Item *d)* of Clause 4 for use with direct voltages. Such a voltmeter may also be used for the measurement of alternating voltages. By a suitable choice of frequency of the capacitance variation and its phase angle relative to the voltage to be measured the peak value or any intermediate value can be determined.

f) Instrument used with series resistance

An alternating current measuring instrument is connected in series with a stable high ohmic value resistor.

11. Systems for measuring the amplitude of harmonics*a) Oscilloscope used with voltage divider*

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

b) Instrument used with filter

A filter is used to suppress the fundamental component of the voltage and the r.m.s. value of the residual harmonics is measured with an appropriate instrument. Alternatively, but with less accuracy, the peak value of the combined harmonics may be measured.

c) Wave analyser used with voltage divider

This system permits separate measurement of the r.m.s. value of the fundamental and each harmonic.

12. Determination of voltage ratios and scale factors*a) Instrument used with voltage transformer*

Methods for determining the ratio of voltage transformers are covered in IEC Publication 186, Voltage Transformers.

b) Instrument used with voltage dividers

Methods for determining the ratio of voltage dividers are described in Clause 17.

c) Electrostatic voltmeter and generating voltmeter

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

d) Instrument used with series resistance

Methods for calibrating systems of this type are described in Item *a)* of Clause 6. However, the impedance of this resistor and the scale factor should be determined within the frequency range of the alternating voltages to be measured.

13. Determination of the amplitude-frequency response of a measuring system

To determine the amplitude-frequency response of a measuring system, a sinusoidal voltage is applied between its input terminals. The ratio of the output to the input amplitudes is recorded as a function of frequency. The range of frequencies should extend from a low value to at least the highest of importance present in the voltage to be measured. The measurements are usually made at a low value of low input voltage.

14. Possible sources of errors and precautions

Due to the high impedances of some voltage dividers and series impedance elements, the effects of corona and stray capacitances may result in serious errors. Such errors can often be minimized by the use of suitably dimensioned high-voltage electrodes and guard circuits. To avoid such effects on capacitor dividers, it is recommended that, when the capacitor is not effectively shielded, the total series capacitance in picofarads be at least 30 to 40 times its overall length in metres.

Errors may also be caused by resistors which have significant voltage or temperature coefficients and by instruments which are subject to drift.

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

When a high-voltage series capacitor is used for voltage measurement, special protection of the measuring instruments is necessary during disruptive discharge tests. Disruptive discharge of a test object connected in parallel with measuring systems of this type results in the application of fast rising current surges to the rectifiers and instruments, which should be suitably protected.

Overstressing of components in measuring equipment upon disruptive discharge of a test object, or measuring errors due to partial discharges, can occur in a measuring system having a high-frequency response appreciably in excess of its response in the low-frequency range. These phenomena are usually associated with the presence of stray inductances.

SECTION FOUR – MEASUREMENT OF IMPULSE VOLTAGES

15. General

Measuring systems for lightning and switching impulse voltages must be capable of recording much higher rates of change of voltage than those used for measuring other types of high voltage. Consequently, the components of the system should be specifically designed to have a good transient response. Therefore, a large portion of this section deals with methods for determining the response characteristics of measuring systems and the errors introduced by an inadequate response. A circuit used for checking the response characteristic of a measuring system is shown in Figure 1, page 66. Other circuits are also applicable.

It is also important that the measuring system does not load the generating system so heavily that it is prevented from developing the required high rates of change of voltage across the test object.

The induced voltages from heavy currents, or voltages outside of the measuring system, are not taken into account when considering the response and the measuring errors. Special care should be taken when the result of response measurements are applied to tests with heavy currents.

It should be realized that the voltage across the test object is rarely identical in all respects to that across the voltage divider.

16. Measuring system components

Most high-voltage impulse measuring systems (except sphere-gaps) consist of a voltage divider, an oscilloscope or an indicating instrument or both, high-voltage leads, low-voltage measuring cables and earth return circuits. A high-voltage damping resistor may also be included. Important features of these components are explained in the following sub-clauses.

16.1 *Voltage divider*

Most high-voltage dividers have distributed stray capacitances to earth and to neighbouring earthed or live objects. In resistor dividers, these capacitances affect the response characteristics since they must be charged and discharged through the divider resistance; in capacitor dividers, the stray capacitances affect the scale factor of the system.

The effect of stray capacitance can be reduced in resistor dividers by keeping the resistance as low as possible without unduly loading the generating system and by using shielding electrodes at the high-voltage end of the divider. These electrodes provide a capacitive path for charging the stray capacitance to earth.

In capacitor dividers, the capacitance of the divider should be large enough to minimize the effect of stray capacitance. Capacitor dividers for rapidly changing impulses may have large overshoots or oscillations in their output due to parasitic inductances in the low-voltage arm.

Mixed dividers consist of both capacitive and resistive elements. In such dividers, the effect of stray capacitance depends on the manner in which the component parts are connected.

16.2 *High-voltage lead*

The length, position and diameter of the lead connecting the high-voltage terminal of the voltage divider to the high-voltage terminal of the test object may all influence the performance of the measuring system. For any particular measurement, the length of the lead should be stated and it should be within the range of lengths for which the measuring system was calibrated. When important, its position should be approximately the same for a test as during calibration.

Ideally, the diameter of the lead should be large enough to prevent corona since corona on the lead can affect the performance of the measuring system. When corona cannot be prevented, it is better to use a small diameter lead. Vigorous discharges in the vicinity of the divider should be avoided.

The high-voltage lead should normally be connected directly to the high-voltage terminal of the test object and not to the impulse generator or any point on the interconnecting lead. This avoids inclusion in the measurement of the inductive voltage drop in this lead. However, when measuring full standard lightning impulses or impulses chopped on the tail, it can in general be

assumed that the error due to connecting the divider to an intermediate point on the lead between the generator and test object is negligible if the condition $\sqrt{LC} \leq 0.05 \mu\text{s}$ is fulfilled. In this relationship, L is the inductance in microhenrys of that part of the lead which is between the divider and the test object (roughly $1 \mu\text{H/m}$) and C is the effective capacitance of the test object in microfarads. The total length of lead between the voltage divider and the test object is then considered to be the high-voltage lead of the measuring system.

16.3 *Damping resistor*

A resistor of very low inductance may be inserted in the high-voltage lead to damp oscillations. This resistor may either be located close to the divider or at the input end of the high-voltage lead. In the first case the resistor is considered to be a part of the divider and the system is then described as a two-component system. In the second case the system is described as a three-component system.

Whatever the position of the resistor, its value must be taken into account when determining the ratio of the system.

The resistor may have an appreciable influence on the response of the measuring system. Only two-component systems are dealt with in this application guide.

16.4 *Oscilloscope*

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

It is important that the deflection plates of the oscilloscope remain under the same conditions of earthing and biasing during the calibration and during the recording of the impulse voltages. Impulse oscilloscopes are not normally equipped with amplifiers and the leads to the deflection plates are kept as short as possible to obtain good high-frequency performance. Oscilloscopes with amplifiers are quite acceptable if they have a sufficiently fast response and their voltage measuring accuracy is sufficiently high. However, such instruments are especially sensitive to disturbances.

The oscilloscope is normally provided with an input connector for the coaxial cable from the voltage divider. The input impedance as measured at this connector should either match the characteristic impedance of the coaxial cable or be as high as possible depending on the type of the divider (see Sub-clause 16.6). Sometimes, both possibilities are provided for. In either case, the input capacitance of the oscilloscope should be kept to a minimum. The instrument may also include an internal attenuator to provide a stepwise division of voltage between the input connector and the deflection plates.

16.5 *Peak voltmeter*

The peak voltmeter is an instrument which usually functions by charging a capacitor through rectifiers, to a voltage which is proportional to the peak value of the impulse to be measured. The charge is retained on the capacitor and is read by means of a very high-impedance amplifier plus a recording or indicating instrument which is incorporated into the device. Such a device has an error which depends on the shape of the impulse to be measured and should be determined experimentally. The input impedance of the instrument is subject to the same restrictions

as noted for the oscilloscope. It should be noted that most instruments of this type have been found to be very subject to interference, especially when measuring impulses which are sharply chopped.

Note. – It is important to check the overall scale factor, the stability, the response characteristics and the sensitivity to disturbances both for impulse oscilloscopes and peak voltmeters. Methods for this checking are under consideration.

16.6 *Coaxial cable and matching devices*

Any measuring cable on the low voltage side of a measuring system should be coaxial and of the high-frequency type. The dielectric loss of the insulation and the resistance of the inner conductor of the cable and that of the sheath may introduce errors. It is essential that the cables be matched at one or both ends to prevent multiple reflections which might result in measurement errors.

If the cable is connected to two or more instruments at the same time and the length of the additional connecting cables is not negligible with respect to that of the main cable, a matching device should be inserted and all cables matched. When the lengths of the additional cables are negligible no matching devices are used and only one cable is matched.

With resistor dividers, the cable is normally matched at the instrument end and sometimes at both ends (see Figure 2a, page 66). Any attenuator or connecting device inserted in the cable should match the cable impedance. When capacitor dividers are used, the cable is usually matched only at the divider end by connecting the matching impedance in series with the cable (see Figure 2b, page 66). Any attenuator or connecting device inserted in the cable should have an input impedance as high as possible. Other methods of matching may be used provided that the response of the system meets the requirements specified in Clause 23.

16.7 *Earth returns*

There are normally several points in the impulse generating and measuring systems which are interconnected and connected to the earth terminal of the test object. It is important that the impedance between all of these points be kept to a minimum. Special care is necessary in areas of heavy earth currents, that is at the earth terminals of the test object, of the impulse generator, and of any front capacitor. This reduction of impedance may be accomplished by the use of earth return conductors consisting of large non-magnetic metal sheets or by making short earth connections to a large metal sheet or mesh in or on the floor of the test area.

17. **Determination of voltage divider ratios and scale factors**

The scale factor of a measuring system is usually obtained by multiplying the voltage ratio of the dividers by the sensitivity of the instrument. This sensitivity is determined by conventional methods.

Various methods are available for the determination of the ratio:

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

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

In addition to the determination of the ratio it is normally necessary to check that the voltage ratio is constant within $\pm 1\%$ for the region of times to peak for which the divider is intended to be used, and does not change more than 5% for the longest time to half value to be considered. This check should be done by means of the step response or by comparison with an approved measuring system during the application of the appropriate impulse shapes.

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

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

18. Response of a measuring system

The accuracy of an impulse measurement can best be evaluated by using some form of generalized response of the measuring system. The type of response which has been selected for impulse measuring systems is the unit step response.

In principle, the step response of an impulse voltage measuring system is the oscillogram obtained when a step voltage is applied between the two input terminals. In practice, the system is modified and an approximate step response called the “experimental unit step response” is obtained.

This response can be used to obtain certain parameters of the true response which are useful for determining the accuracy of a measurement. These parameters are listed below together with an indication of their applicability. Their determination from experimental step response oscillograms is described in Clause 20. They can also be obtained with the use of a sphere-gap as described in Clause 21.