Measurement of High Voltages and Currents

The devices and instruments for measurement of high voltages and currents differ vastly from the low voltage and low current devices.

MEASUREMENT OF HIGH DIRECT CURRENT VOLTAGES

High voltages can be measured in a variety of ways. Direct measurement of high voltages is possible up to about 200 kV, and several forms of voltmeters have been devised which can be connected directly across the test circuit. High Voltages are also measured by stepping down the voltage by using transformers and potential dividers. The sparkover of sphere gaps and other gaps are also used, especially in the calibration of meters in high voltage measurements. Transient voltages may be recorded through potential dividers and oscilloscopes. Lightning surges may be recorded using the Klydonograph.

Direct Measurement of High Voltages

1 Electrostatic Voltmeters

*Principle is used in electrostatic voltmeter?*

If the electric field is produced by the voltage \( V \) between a pair of parallel plate disc electrodes, the force \( F \) on an area \( A \) of the electrode, for which the field gradient \( E \) is the same across the area and perpendicular to the surface.

One of the direct methods of measuring high voltages is by means of electro-static voltmeters. For voltages above 10 kV, generally the attracted disc type of electrostatic voltmeter is used. When two parallel conducting plates (cross section area \( A \) and spacing \( x \)) are charged \( q \) and have a potential difference \( V \), then the energy stored in the is given by

\[
\text{Energy stored } W = \frac{1}{2} C V^2 \quad \text{so that change } d W = \frac{1}{2} V^2 \quad dC = F \quad d x \\
\text{Force } F = \frac{1}{2} V^2 \quad (dC/dx) \quad \text{Newton} = 1/2 \ A \varepsilon (V^2/x^2).
\]

It is thus seen that the force of attraction is proportional to the square of the potential difference applied, so that the meter reads the square value (or can be marked to read the rms value). Electrostatic voltmeters of the attracted disc type may be connected across the high voltage circuit directly to measure up to about 200 kV, without the use of any potential.

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divider or other reduction method. [The force in these electrostatic instruments can be used to measure both a.c. and d.c. voltages.

2 Sphere gaps

The sphere gap method of measuring high voltage is the most reliable and is used as the standard for calibration purposes. The breakdown strength of a gas depends on the ionisation of the gas molecules, and on the density of the gas. As such, the breakdown voltage varies with the gap spacing; and for a uniform field gap, a high consistency could be obtained, so that the sphere gap is very useful as a measuring device. By precise experiments, the breakdown voltage variation with gap spacing, for different diameters and distances, have been calculated and represented in charts. In the measuring device, two metal spheres are used, separated by a gas-gap. The potential difference between the spheres is raised until a spark passes between them. The breakdown strength of a gas depends on the size of the spheres, their distance apart and a number of other factors. A spark gap may be used for the determination of the peak value of a voltage wave, and for the checking and calibrating of voltmeters and other voltage measuring devices. The density of the gas (generally air) affects the spark-over voltage for a given gap setting. Thus the correction for any air density change must be made. The air density correction factor \( \delta = 0.386 P/(273 + t) \)

The spark over voltage for a given gap setting under the standard conditions (760 torr pressure and at 20\(^o\)C) must be multiplied by the correction factor to obtain the actual spark-over voltage. The breakdown voltage of the sphere gap is almost independent of humidity of the atmosphere, but the presence of dew on the surface lowers the breakdown voltage and hence invalidates the calibrations.

The breakdown voltage characteristic has been determined for similar pairs of spheres (diameters 62.5 mm, 125 mm, 250 mm, 500 mm, 1 m and 2 m). When the gap distance is increased, the uniform field between the spheres becomes distorted, and accuracy falls.

The limits of accuracy are dependant on the ratio of the spacing \( d \) to the sphere diameter \( D \), as

\[ d < 0.5 \, D, \text{ accuracy} = \pm 3 \% \quad \text{and} \quad 0.75 \, D > d > 0.5 \, D, \text{ accuracy} = \pm 5 \% \]
The breakdown voltage characteristic is also dependent on the polarity of the high voltage sphere in the case of asymmetrical gaps (i.e., gaps where one electrode is at high voltage and the other at a low voltage or earth potential). If both electrodes are at equal high voltage of opposite polarity (i.e., $+\frac{1}{2}V$ and $-\frac{1}{2}V$), as in a symmetrical gap, then the polarity has no effect. In the case of the asymmetrical gap, there are two breakdown characteristics; one for the positive high voltage and the other for the negative high voltage. Since the breakdown is caused by the flow of electrons, when the high voltage electrode is positive, a higher voltage is generally necessary for breakdown than when the high voltage electrode is negative. However, when the gaps are very far apart, then the positive and the negative characteristics cross over due to various space charge effects. But this occurs well beyond the useful operating region. Under alternating voltage conditions, breakdown will occur corresponding to the lower curve (i.e., in the negative half cycle under normal gap spacings). Thus under normal conditions, the a.c. characteristic is the same as the negative characteristic. In sphere gaps used in measurement, to obtain high accuracy, the minimum clearance to be maintained between the spheres and the neighbouring bodies and the diameter of shafts are also specified, since these also affect the accuracy (figure 6.5). There is also a tolerance specified for the radius of curvature of the spheres. "The length of any diameter shall not differ from the correct value by more than 1% for spheres of diameter up to 100 cm or more than 2% for larger spheres". Peak values of voltages may be measured from 2 kV up to about 2500 kV by means of spheres. One sphere may be earthed with the other being the high voltage electrode, or both may be supplied with equal positive and negative voltages with respect to earth (symmetrical gap). When spark gaps are to be calibrated using a standard sphere gap, the two gaps should not be connected in parallel. Equivalent spacing should be determined by comparing each gap in turn with a suitable indicating instrument. Needle gaps may also be used in the measurement of voltages up to about 50 kV, but errors are caused by the variation of the sharpness of the needle gaps, and by the corona forming at the points before the gap actually sparks over. Also the effect of the variation of the humidity of the atmosphere on such gaps is much greater. Usually, a resistance is used in series with the sphere gap, of about 1ohm/V sparkover conditions to about a maximum of 1 A. However for impulse measurements, a series resistance must not be used since this causes a large drop across the resistance. In measuring impulse voltages, since the breakdown does not occur at exactly the same value of voltage each time, what is generally specified is the 50% breakdown value. A number of impulses of the same value...
is applied and a record is kept of the number of times breakdown occurs, and a histogram is plotted with the peak value of the impulse voltage and the percentage of breakdown.

The factors that are influencing the peak voltage measurement using sphere gap are

(i) Nearby earthed objects
(ii) Atmosphere conditions
(iii) Influence of humidity
(iv) Irradiation
(v) Polarity and rise time of voltage waveform
(vi) Switching surge

3 GENERATING VOLTMETER (GVM)

A generating voltmeter is a variable capacitor voltage generator which generates current proportional to the voltage to be measured. It provides loss free measurement of D.C and A.C voltages. It is driven by a synchronous motor and does not absorb power or energy from the voltage measuring source.

Whenever the source loading is not permitted or when direct connection to the high voltage source is to be avoided, the generating principle is employed for the measurement of high voltages. A generating voltmeter is a variable capacitor electrostatic voltage generator which generates current proportional to the voltage to be measured. Similar to electrostatic voltmeter the generating voltmeter provides loss free measurement of d.c.
and a.c. voltages. The device is driven by an external constant speed motor and does not absorb power or energy from the voltage measuring source. In the fig shown below

$H$ is a high voltage electrode and the earthed electrode is subdivided into a sensing or pick up electrode $P$, a guard electrode $G$ and a movable electrode $M$, all of which are at the same potential. The high voltage electrode $H$ develops an electric field between itself and the electrodes $P$, $G$ and $M$. The electric field density

The high voltage electrode and the grounded electrode in fact constitute a capacitance system. The capacitance is, however, a function of time as the area $A$ varies with time and, therefore, the charge $q(t)$ is given as $q(t)=C(t)V(t)$

A GVM which employs rotating vanes for variation of capacitance. The high voltage electrode is connected to a disc electrode $D_3$ which is kept at a fixed distance on the axis of the other low voltage electrodes $D_2$, $D_1$, and $D_0$. The rotor $D_0$ is driven at a constant speed by a synchronous motor at a suitable speed. The rotor vanes of $D_0$ cause
periodic change in capacitance between the insulated disc D2 and the high voltage electrode D3. The number and shape of vanes are so designed that a suitable variation of capacitance (sinusoidal or linear) is achieved. The a.c. current is rectified and is measured using moving coil meters. If the current is small an amplifier may be used before the current is measured.

Advantages of generating Voltmeter: (i) Scale is linear and extension of voltage range is easy

(ii) Source loading is zero

(iii) It can measure wide range of voltages

(iv) There is no connection to H.V.electrode.

Disadvantage: (i) need calibration

(ii) Careful construction is needed

(iii) Disturbance in position and mounting of the electrodes make the calibration invalid.

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MEASUREMENT OF HIGH a.c. AND IMPULSE VOLTAGES:

Measurement of high a.c. voltages employ conventional methods like series impedance voltmeters, potential dividers, potential transformers, or electrostatic voltmeters. But their designs are different from those of low voltage meters, as the insulation design and source loading are the important criteria. When only peak value measurement is needed, peak voltmeters and sphere gaps can be used. Often, sphere gaps are used for calibration purposes. Impulse and high frequency a.c. measurements invariably use potential dividers with a cathode ray oscillograph for recording voltage waveforms. Sphere gaps are used when peak values of the voltage are only neede and also for calibration purposes.

.1 Series Impedance Voltmeters

For power frequency a.c. measurements the series impedance may be a pure resistance or a reactance. Since resistances involve power losses, often a capacitor is preferred as a series reactance. Moreover, for high resistances, the variation of resistance with temperature is a
problem, and the residual inductance of the resistance gives rise to an impedance different from its ohmic resistance. High resistance units for high voltages have stray capacitances and hence a unit resistance will have an equivalent circuit as shown in Fig. At any frequency CD of the a.c. voltage, the impedance of the resistance R is

$$Z = \frac{R + j\omega L}{(1 - \frac{\omega^2}{LC}) + j\omega CR}$$

![Simplified lumped parameter equivalent circuit of a high ohmic resistance R](image)

- $L$ — Residual inductance
- $C$ — Residual capacitance

If $\omega L$ and $\omega C$ are small compared to R,

$$Z = R \left[ 1 + j \left( \frac{\omega L}{R} - \omega CR \right) \right]$$

and the total phase angle is

$$\varphi = \left( \frac{\omega L}{R} - \omega CR \right)$$

This can be made zero and independent of frequency, if $L/C = R^2$

For extended and large dimensioned* resistors, this equivalent circuit is not valid and each elemental resistor has to be approximated with this equivalent circuit. The entire resistor unit then has to be taken as a transmission line equivalent, for calculating the effective resistance. Also, the ground or stray capacitance of each element influences the current flowing in the unit, and the indication of the meter results in an error. The equivalent circuit of a high voltage resistor neglecting inductance and the circuit of compensated series resistor using guard and timing resistors is shown in Figs. Stray ground capacitance effects can be removed by shielding the resistor? by a second surrounding spiral $Rs>$ which shunts the
actual resistor but does not contribute to the current through the instrument. By tuning the resistors \( R \) the shielding resistor end potentials may be adjusted with respect to the actual measuring resistor so that the resulting compensation currents between the shield and the measuring resistors provide a minimum phase angle.

![Diagram of a capacitor network used for high voltage measurements](image)

(a) Extended series resistance with inductance neglected

- \( C_g \) — Stray capacitance to ground
- \( C_3 \) — Winding capacitance

(b) Series resistance with guard and tuning resistances

- \( R \) — Series resistor
- \( R_s \) — Guard resistor
- \( R_a \) — Tuning resistor

**Series Capacitance Voltmeter**

To avoid the drawbacks pointed out earlier, a series capacitor is used instead of a resistor for a.c. high voltage measurements. The schematic diagram is shown in the Fig.
The current $I_c$ through the meter is: $I_c = j\omega CV$

where, $C$ = capacitance of the series capacitor,  
$\omega$ = angular frequency, and  
$V$ = applied a.c. voltage.

If the a.c. voltage contains harmonics, error due to changes in series impedance occurs. The rms value of the voltage $V$ with harmonics is given by

$$V = \sqrt{V_1^2 + V_2^2 + \ldots + V_n^2}$$

where $V_1, V_2 \ldots V_n$ represent the rms value of the fundamental, second... and nth harmonics.

The currents due to these harmonics are

$$I_1 = \omega CV_1$$  
$$I_2 = 2\omega CV_2, \ldots, \text{ and}$$  
$$I_n = n\omega CV_n$$

Hence, the resultant rms current is:

$$I = \omega C \left( V_1^2 + 4V_2^2 + \ldots + n^2V_n^2 \right)^{1/2}$$
With a 10% fifth harmonic only, the current is 11.2% higher, and hence the error is 11.2% in the voltage measurement. This method is not recommended when a.c. voltages are not pure sinusoidal waves but contain considerable harmonics.

**Capacitance Potential Dividers and Capacitance Voltage Transformers**

![Capacitance potential divider diagram](image)

The errors due to harmonic voltages can be eliminated by the use of capacitive voltage dividers with an electrostatic voltmeter or a high impedance meter such as a V.T.V.M. If the meter is connected through a long cable, its capacitance has to be taken into account in calibration. Usually, a standard compressed air or gas condenser is used as C1 and C2 may be any large capacitor (mica, paper, or any low loss condenser). C1 is a three terminal capacitor and is connected to C2 through a shielded cable, and C2 is completely shielded in a box to avoid stray capacitances. The applied voltage V1 is given by

\[ V_1 = V_2 \left( \frac{C_1 + C_2 + C_m}{C_1} \right) \]

where Cm is the capacitance of the meter and the connecting cable and the leads and V2 is the meter reading.
Capacitance Voltage Transformer—CVT

Capacitance divider with a suitable matching or isolating potential transformer tuned for resonance condition is often used in power systems for voltage measurements. This is often referred to as CVT. In contrast to simple capacitance divider which requires a high impedance meter like a V.T.V.M. or an electrostatic voltmeter, a CVT can be connected to a low impedance device like a wattmeter pressure coil or a relay coil. CVT can supply a load of a few VA. The schematic diagram of a CVT with its equivalent circuit is given in Fig. C1 is made of a few units of high voltage condensers, and the total capacitance will be around a few thousand picofarads as against a gas filled standard condenser of about 100 pF. A matching transformer is connected between the load or meter M and C2. The transformer ratio is chosen on economic grounds, and the h.v. winding rating may be 10 to 30 kV with the Lv. winding rated from 100 to 500 V. The value of the tuning
choke L is chosen to make the equivalent circuit of the CVT purely resistive or to bring resonance condition. This condition is satisfied when

\[ \omega (L + L_T) = \frac{1}{\omega(C_1 + C_2)} \]

where,

- \( L \) = inductance of the choke, and
- \( L_T \) = equivalent inductance of the transformer referred to h.v. side.

The voltage \( V_2 \) (meter voltage) will be in phase with the input voltage \( V_1 \). The phasor diagram of CVT under resonant conditions is shown in Fig. The meter is taken as a resistive load, and \( X' \)

\( m \) is neglected. The voltage across the load referred to the divider side will be

\[ V'_2 = (I'_m R'_m) \text{ and } V'_C = V'_2 + I_m(R_e + X_e). \]

It is clear from the phasor diagram that \( V_1 \) (input voltage) = \( V_{C1} + V_{C2} \) and is in phase with \( V'_2 \), the voltage across the meter. \( R_e \) and \( X_e \) include the potential transformer resistance and leakage reactance. Under this condition, the voltage ratio becomes

\[ a = \frac{V_1}{V_2} = (V_{C1} + V_{Ri} + V'_2)/V'_2 \]

The advantages of a CVT are:

(i) simple design and easy installation,
(ii) can be used both as a voltage measuring device for meter and relaying purposes and also as a coupling condenser for power line carrier communication and relaying.
(iii) frequency independent voltage distribution along elements as against conventional magnetic potential transformers which require additional insulation design against surges, and
(iv) provides isolation between the high voltage terminal and low voltage metering.

The disadvantages of a CVT are:

(i) the voltage ratio is susceptible to temperature variations, and
(ii) the problem of inducing ferro-resonance in power systems.
Resistance Potential Dividers

Resistance potential dividers suffer from the same disadvantages as series resistance voltmeters for a.c. applications. Moreover, stray capacitances and inductances associated with the resistances make them inaccurate, and compensation has to be provided. Hence, they are not generally used.

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NON-DESTRUCTIVE TESTING OF MATERIALS AND ELECTRICAL APPARATUS

In order to ensure an economic power-supply system with a high level of reliability, it is important to be able to monitor the dielectric parameters of the various insulations being utilized – when new and in service. Present power systems are ageing significantly and in many cases 40 per cent of the equipment is older than the conventional ‘design life’ of 25 years. The condition of high voltage electrical insulation systems used in power cables, power transformers and generators is influenced by a number of manufacturing and operating variables which affect performance and failure

Nondestructive testing - NDT - use test methods to examine an object, material or system without impairing its future usefulness. Non-destructive testing is often required to verify the quality of a product or a system. Commonly used techniques are

AET - Acoustic Emission Testing
ART - Acoustic Resonance Testing
ET - Electromagnetic Testing
IRT - Infrared Testing
LT - Leak Testing
MT - Magnetic Particle Testing
PT - Dye Penetrant Testing
RT - Radiographic Testing
UT - Ultrasonic Testing

VT - Visual Testing (VI - Visual Inspection)

Impedance measurements are a basic means of evaluating electronic components and materials. Every material has a unique set of electrical characteristics that are dependent on its dielectric or insulation properties. Accurate measurements of these properties can provide valuable information to ensure an intended application or maintain a proper manufacturing process.

**Measurement of dc insulation resistance, volume resistance, and surface resistance.**

From such measurements and the geometric dimensions of specimen and electrodes, both volume and surface resistivity of electrical insulating materials can be calculated, as well as the corresponding conductances and conductivities.

The dc resistance test is used to measure the direct-current (dc) resistance of resistors, electromagnetic windings of components, conductors, etc..

When a dielectric is subjected to a steady state static electric field \( E \) the current density \( J_c \) is given by

\[ J_c = \sigma E \]

Assuming a cuboid of the insulating material with thickness \( d \) and area \( A \), then

\[ \text{Current } I = J_c A \text{ and power loss } = VI = VJ_c A = V \sigma E A = V \sigma AVd = \sigma E^2. \text{ Volume.} \]

Therefore, specific dielectric loss = \( \sigma E^2 \) Watts/m3.

The conductivity of the insulating materials viz liquid and solid depends upon the temperature and the moisture contents. The leakage resistance \( R_0 (\sigma) \) of an insulating material is determined by measuring the current when a constant d.c. voltage is applied. Since the current is a function of time as different mechanisms are operating simultaneously, so to measure only the conduction current it is better to measure the current about 1 min after the voltage is switched on. For simple geometries of the specimen (cuboid or cube) specific resistivity (\( p = 1/\sigma \)) can be calculated from the leakage resistance measured. If
I is the conduction current measured and V the voltage applied, the leakage resistance is given by $R = \frac{V}{I} = \frac{d}{\sigma A}$, where $d$ is the thickness of the specimen and $A$ is the area of section.

The d.c. voltage of 100 volt or 1000 volt is applied between electrode 1 and the earth. The measuring electrode 2 is earthed through a sensitive ammeter. The third electrode known as guard ring electrode surrounds the measuring electrode and is directly connected to ground so as to eliminate boundary field effects and surface currents. The width of the guard electrode should be at least twice the thickness of the specimen and the unguarded electrode (1) must extend to the outer edge of the guard electrode. The gap between electrode 2 and 3 should be as small as possible. A thin metallic foil usually of aluminium or lead of about 20 $\mu$m thickness is placed between the electrodes and specimen for better contact. The specific conductivity for most of the insulating material lies in the range of $10^{-16}$ to $10^{-10}$ S/cm, which gives currents to be measured of these specimen to be of the order of picoamperes or nanoamperes. The measuring leads should be appropriately and carefully screened. The measurement of conduction current using d.c. voltage not only provides information regarding specific resistivity of the material but it gives an idea of health of the insulating material. If conduction currents are large, the insulating properties of the material are lost. This method, therefore, has proved very good in the insulation control of large electrical machines during their period of operation.
Measurement of Dielectric Constant

The measurement of dielectric constant, also known as relative permittivity of a material, is one of the most popular methods of evaluating insulators such as rubber, plastics, and powders. It is used to determine the ability of an insulator to store electrical energy. The complex dielectric constant consists of a real part \( k' \), which represents the storage capability and an imaginary part \( D \), which represents the loss.

Dielectric constant measurements can be performed easier and faster than chemical or physical analysis techniques making them an excellent material analysis tool.

Measurement of Dissipation Factor

Dissipation factor \( D \) is defined as the ratio of an insulating materials resistance to its capacitive reactance at a specified frequency. It measures the inefficiency or loss of the material, is always greater than 0, but usually much smaller than the dielectric constant. \( D \) measurements are an excellent means of quality control which can yield indication of contamination or deterioration. For example, if we wanted to check the purity of epoxy or some raw material for consistency in a production run why not just measure the \( D \). Excessive moisture would increase the dissipation factor value telling us something has changed as compared to previously established values.
The dielectric conductivity takes into account all the three power dissipative processes including the one which is frequency dependent. Fig. 8.2 shows two equivalent circuits representing the electrical behaviour of insulating materials under a.c. voltages, losses have been simulated by resistances.

Normally the angle between V and the total current in a pure capacitor is 90°. Due to losses, this angle is less than 90°. Therefore, $\delta$ is the angle by which the voltage and charging current fall short of the 90° displacement.

$$\tan\delta = 1/(\omega C_p R_p)$$

whereas for series circuit $\tan\delta = (\omega C_s R_s)$

**HIGH VOLTAGE SCHERING BRIDGE**

The bridge is widely used for capacity and dielectric loss measurement of all kinds of capacitances, for instance cables, insulators and liquid insulating materials. We know that most of the high voltage equipments have low capacitance and low loss factor. This bridge is then more suitable for measurement of such small capacitance equipments as the bridge uses either high voltage or high frequency supply. If measurements for such low capacity equipments is carried out at low voltage, the results so obtained are not accurate.
Special features of the bridge

1. High Voltage supply
2. Screened Standard Capacitor
3. Large impedance of arm I & II
4. Null Detector
5. Automatic Guard Potential Regulator

The bridge is balanced by successive variation of R1 and C2 until on the oscilloscope (Detector) a horizontal straight line is observed.
Partial discharge is defined as localised discharge process in which the distance between two electrodes is only partially bridged i.e., the insulation between the electrodes is partially punctured. Partial discharges may originate directly at one of the electrodes or occur in a cavity in the dielectric. Some of the typical partial discharges are:

(i) **Corona or gas discharge.** These occur due to non-uniform field on sharp edges of the conductor subjected to high voltage especially when the insulation provided is air or gas or liquid.

(ii) Surface discharges and discharges in laminated materials on the interfaces of different dielectric material such as gas/solid interface as gas gets overstressed \( \varepsilon_r \) times the stress on the solid material (where \( \varepsilon_r \) is the relative permittivity of solid material) and ionization of gas results

(iii) **Cavity discharges:** When cavities are formed in solid or liquid insulating materials the gas in the cavity is overstressed and discharges are formed.

(iv) **Treeing Channels:** High intensity fields are produced in an insulating material at its sharp edges and this deteriorates the insulating material. The continuous partial discharges so produced are known as Treeing Channels.

External partial discharge is the process which occurs external to the equipment e.g. on overhead lines, on armature etc.
Internal Partial Discharge

Internal partial discharge is a process of electrical discharge which occurs inside a closed system (discharge in voids, treeing etc). This kind of classification is essential for the PD measuring system as external discharges can be nicely distinguished from internal discharges. Partial discharge measurement have been used to assess the life expectancy of insulating materials. Even though there is no well defined relationship, yet it gives sufficient idea of the insulating properties of the material. Partial discharges on insulation can be measured not only by electrical methods but by optical, acoustic and chemical method also. The measuring principles are based on energy conversion process associated with electrical discharges such as emission of electromagnetic waves, light, noise or formation of chemical compounds. The oldest and simplest but less sensitive is the method of listening to hissing sound coming out of partial discharge. A high value of loss factor $\tan \delta$ is an indication of occurrence of partial discharge in the material. This is also not a reliable measurement as the additional losses generated due to application of high voltage are localised and can be very small in comparison to the volume losses resulting from polarization process. Optical methods are used only for those materials which are transparent and thus not applicable for all materials. Acoustic detection methods using ultrasonic transducers have, however, been used with some success. The most modern and the most accurate methods are the electrical methods. The main objective here is to separate impulse currents associated with PD from any other phenomenon.

**The basic PD test circuit**

For the evaluation of the fundamental quantities related to a PD pulse we simulate the test object, as usual, by the simple capacitor arrangement as shown in Fig. comprising solid or fluid dielectric materials between the two electrodes or terminals A and B, and a gas-filled cavity. The electric field distribution within this test object is here simulated by some partial capacitances, which is possible as long as no space charges disturb this distribution. Electric field lines within the cavity are represented by $C_c$ and those starting or ending at the cavity walls form the two capacitances $C_b'$ and $C_b''$ within the solid or fluid dielectric. All field lines outside the cavity are represented by

$$C_a = C_a' + C_a''$$

Due to realistic geometric dimensions involved $C_b = C_b'/ (C_b' + C_b'')$ the magnitude of the capacitances will then be controlled by the inequality $C_a \gg C_c \gg C_b$. 
High Voltage Testing of Electrical Apparatus

Electrical equipment must be capable of withstanding overvoltages during operation. Thus by suitable testing procedure we must ensure that this is done. High voltage testing can be broadly classified into testing of insulating materials (samples of dielectrics) and tests on completed equipment. The tests carried out on samples of dielectric consist generally of the measurement of permittivity, dielectric loss per unit volume, and the dielectric strength of the material. The first two can be measured using the High Voltage Schering Bridge. The tests carried out on completed equipment are the measurement of capacitance, the power factor or the total dielectric loss, the ultimate breakdown voltage and the flash-over voltage. The breakdown voltage tests on completed equipment is only done on a few samples since it permanently damages and destroys the equipment from further use. However since all equipment have to stand up to a certain voltage without damage under operating conditions, all equipment are subjected to withstand tests on which the voltage applied is about twice the normal voltage, but which is less than the breakdown voltage.

In alternating voltage system, a careful choice of the characteristics of the testing transformer is essential. It is known that the flash over voltage of the insulator in air or in any insulating fluid depends upon the capacitance of the supply system. This is due to
the fact that a voltage drop may not maintain preliminary discharges or breakdown. It is, therefore, suggested that a capacitance of at least 1000 pF must be connected across the insulator to obtain the correct flash over or puncture voltage and also under breakdown condition (a virtual short circuit) the supply system should be able to supply at least 1 amp for clean and 5 amp for polluted insulators at the test voltage. There are some difficult problems with impulse testing equipments also especially when testing large power transformers or large reactors or large cables operating at very high voltages.

TESTING OF OVERHEAD LINE INSULATORS

High voltage testing of electrical equipment requires two types of tests: (i) Type tests, and (ii) Routine test. Type tests involves quality testing of equipment at the design and development level i.e. samples of the product are taken and are tested when a new product is being developed and designed or an old product is to be redesigned and developed whereas the routine tests are meant to check the quality of the individual test piece. This is carried out to ensure quality and reliability of individual test objects.

High voltage tests include (i) Power frequency tests and (ii) Impulse tests. These tests are carried out on all insulators.

(i) 50% dry impulse flash over test.
(ii) Impulse withstand test.
(iii) Dry flash over and dry one minute test.
(iv) Wet flash over and one minute rain test.
(v) Temperature cycle test.
(vi) Electro-mechanical test.
(vii) Mechanical test.
(viii) Porosity test.
(ix) Puncture test.

(x) Mechanical routine test.

If the test is carried out under artificial rain, it is called wet flash over test. The insulator is subjected to spray of water of following characteristics:

Precipitation rate 3±10% mm/min.

Direction 45° to the vertical

Conductivity of water 100 micro siemens ±10%

Temperature of water Ambient +15°C

The insulator with 50% of the one-min. rain test voltage applied to it, is then sprayed for two minutes, the voltage raised to the one minute test voltage in approximately 10 sec. and maintained there for one minute. The voltage is then increased gradually till flash over occurs and the insulator is then flashed at least four more times, the time taken to reach flash over voltage being in each case about 10 sec. The flash over voltage must not be less than the value specified in specifications.

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TESTING OF BUSHINGS

Bushings are an integral component of high voltage machines. A bushing is used to bring high voltage conductors through the grounded tank or body of the electrical equipment without excessive potential gradients between the conductor and the edge of the hole in the body. The bushing extends into the surface of the oil at one end and the other end is carried above the tank to a height sufficient to prevent breakdown due to surface leakage. Following tests are carried out on bushings:

(i) Power Factor Test

The bushing is installed as in service or immersed in oil. The high voltage terminal of the bushing is connected to high voltage terminal of the Schering Bridge and the tank or earth portion of the bushing is connected to the detector of the bridge. The capacitance and p.f. of
the bushing is measured at different voltages as specified in the relevant specification and the capacitance and p.f. should be within the range specified.

(ii) Impulse Withstand Test

The bushing is subjected to impulse waves of either polarity and magnitude as specified in the standard specification. Five consecutive full waves of standard wave form are applied and if two of them cause flash over, the bushing is said to be defective. If only one flash over occurs, ten additional applications are made. If no flash over occurs, bushing is said to have passed the test.

(iii) Chopped Wave and Switching Surge Test

Chopped wave and switching surge of appropriate duration tests are carried out on high voltage bushings. The procedure is identical to the one given in (ii) above.

(iv) Partial Discharge Test

In order to determine whether there is deterioration or not of the insulation used in the bushing, this test is carried out.

(v) Visible Discharge Test at Power Frequency

The test is carried out to ascertain whether the given bushing will give rise to ratio interference or not during operation. The test is carried out in a dark room. The voltage as specified is applied to the bushing (IS 2099). No discharge other than that from the grading rings or arcing horns should be visible.

(vi) Power Frequency Flash Over or Puncture Test

(Under Oil): The bushing is either immersed fully in oil or is installed as in service condition. This test is carried out to ascertain that the internal breakdown strength of the bushing is 15% more than the power frequency momentary dry withstand test value.

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TESTING OF CIRCUIT BREAKERS
An equipment when designed to certain specification and is fabricated, needs testing for its performance. The general design is tried and the results of such tests conducted on one selected breaker and are thus applicable to all others of identical construction.

Testing of circuit breakers is intended to evaluate

(a) the constructional and operational characteristics, and

(b) the electrical characteristics of the circuit which the switch or the breaker has to interrupt or make. The different characteristics of a circuit breaker or a switch may be summarized as per the following groups.

(i) (a) The electrical characteristics which determine the arcing voltage, the current chopping characteristics, the residual current, the rate of decrease of conductance of the arc space and the plasma, and the shunting effects in interruption.

(b) Other physical characteristics including the media in which the arc is extinguished, the pressure developed or impressed at the point of interruption, the speed of the contact travel, the number of breaks, the size of the arcing chamber, and the materials and configuration of the circuit interruption.

(ii) The characteristics of the circuit include the degree of electrical loading, the normally generated or applied voltage, the type of fault in the system which the breaker has to clear, the time of interruption, the time constant, the natural frequency and the power factor of the circuit, the rate of rise of recovery voltage, the restriking voltage, the decrease in the a.c. component of the short circuit current, and the degree of asymmetry and the d.c. component of the short circuit current,

These tests are called the type tests. These tests are classified as follows:

1. Short circuit tests:

(i) Making capacity test.
(ii) Breaking capacity test.

(iii) Short time current test.

(iv) Operating duty test

2. Dielectric tests:

(i) Power frequency test:

(a) One minute dry withstand test.

(b) One minute wet withstand test.

(ii) Impulse voltage dry withstand test.

3. Thermal test.

4. Mechanical test

TESTING OF ISOLATORS

An isolator or a disconnector is a mechanical switching device, which provides in the open position, an isolating distance in accordance with special requirements. An isolator is capable of opening and closing a circuit when either negligible current is broken or made or when no significant change in the voltage across the terminals of each of the poles of the isolator occurs. It is also capable of carrying currents under normal circuit conditions, and carrying for a specified time, currents under abnormal conditions such as those of a short circuit. Thus, most of the discussion here refers to the testing of circuit breakers.

To assess the above factors, the main tests conducted on the circuit breakers and isolator switches are

(i) the dielectric tests or overvoltage tests,

(ii) the temperature rise tests,

(iii) the mechanical tests, and

(iv) the short circuit tests
Short Circuit Tests

The most important tests carried out on circuit breakers are short circuit tests, since these tests assess the primary performance of these devices, i.e. their ability to safely interrupt the fault currents. These tests consist of determining the making and breaking capacities at various load currents and rated voltages. In the case of isolators, the short circuit tests are conducted only with the limited purpose to determine their capacity to carry the rated short circuit current for a given duration; and no breaking or making current test is done.

The different methods of conducting short circuit tests are:

(I) Direct Tests

(a) using a short circuit generator as the source

(b) using the power utility system or network as the source.

(II) Synthetic Tests

The different methods of conducting short circuit tests are:

Testing of Cables

High voltage power cables have proved quite useful especially in case of HV d.c. transmission. Underground distribution using cables not only adds to the aesthetic looks of a metropolitan city but it provides better environments and more reliable supply to the consumers.

A cable is subjected to following tests:

(i) Bending tests.

(ii) Loading cycle test.

(iii) Thermal stability test.

(iv) Dielectric thermal resistance test.

(v) Life expectancy test.
(vi) Dielectric power factor test.

(vii) Power frequency withstand voltage test.

(viii) Impulse withstand voltage test.

(ix) Partial discharge test.

High Voltage Schering Bridge is used to perform dielectric power factor test on the cable sample. The power factor is measured for different values of voltages e.g. 0.5, 1.0, 1.5 and 2.0 times the rated operating voltages. The maximum value of power factor at normal working voltage does not exceed a specified value (usually 0.01) at a series of temperatures ranging from 15°C to 65°C. The difference in the power factor between rated voltage and 1.5 times the rated voltage and the rated voltage and twice the rated voltage does not exceed a specified value. Sometimes the source is not able to supply charging current required by the test cable, a suitable choke in series with the test cable helps in tiding over the situation.

Partial discharge measurement of cables is very important as it gives an indication of expected life of the cable and it gives location of fault, if any, in the cable. When a cable is subjected to high voltage and if there is a void in the cable, the void breaks down and a discharge takes place. As a result, there is a sudden dip in voltage in the form of an impulse. This impulse travels along the cable as explained in detail in Chapter VI. The duration between the normal pulse and the discharge pulse is measured on the oscilloscope and this distance gives the location of the void from the test end of the cable. However, the shape of the pulse gives the nature and intensity of the discharge. In order to scan the entire length of the cable against voids or other imperfections, it is passed through a tube of insulating material filled with distilled water. Four electrodes, two at the end and two in the middle of the tube are arranged. The middle electrodes are located at a stipulated distance and these are energized with high voltage. The two end electrodes and cable conductor are grounded. As the cable is passed between the middle electrode, if a discharge is seen on the oscilloscope, a defect in this part of the cable is stipulated and hence this part of the cable is removed from the rest of the cable.

TESTING OF POWER TRANSFORMERS
Transformer is one of the most expensive and important equipment in power system. If it is not suitably designed its failure may cause a lengthy and costly outage. Therefore, it is very important to be cautious while designing its insulation, so that it can withstand transient over voltage both due to switching and lightning. The high voltage testing of transformers is, therefore, very important and would be discussed here. Other tests like temperature rise, short circuit, open circuit etc. are not considered here. However, these can be found in the relevant standard specification.

Partial Discharge Test The test is carried out on the windings of the transformer to assess the magnitude of discharges. The transformer is connected as a test specimen similar to any other equipment and the discharge measurements are made. The location and severity of fault is ascertained using the travelling wave theory technique. The measurements are to be made at all the terminals of the transformer and it is estimated that if the apparent measured charge exceeds 104 picocoulombs, the discharge magnitude is considered to be severe and the transformer insulation should be so designed that the discharge measurement should be much below the value of 104 pico-coulombs.

Impulse Testing of Transformer

The impulse level of a transformer is determined by the breakdown voltage of its minor insulation (Insulation between turn and between windings), breakdown voltage of its major insulation (insulation between windings and tank) and the flash over voltage of its bushings or a combination of these. The impulse characteristics of internal insulation in a transformer differs from flash over in air in two main respects. Firstly the impulse ratio of the transformer insulation is higher (varies from 2.1 to 2.2) than that of bushing (1.5 for bushings, insulators etc.). Secondly, the impulse breakdown of transformer insulation in practically constant and is independent of time of application of impulse voltage.

Impulse testing consists of the following steps:

(i) Application of impulse of magnitude 75% of the Basic Impulse Level (BIL) of the transformer under test.

(ii) One full wave of 100% of BIL.

(iii) Two chopped wave of 115% of BIL.

(iv) One full wave of 100% BIL and
(v) One full wave of 75% of BIL.

During impulse testing the fault can be located by general observation like noise in the tank or smoke or bubble in the breather. If there is a fault, it appears on the Oscilloscope as a partial of complete collapse of the applied voltage. Study of the waveform of the neutral current also indicated the type of fault. If an arc occurs between the turns or form turn to the ground, a train of high frequency pulses are seen on the oscilloscope and wave shape of impulse changes. If it is a partial discharge only, high frequency oscillations are observed but no change in wave shape occurs.

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TESTING OF SURGE DIVERTERS

A surge diverter has to be a non-conductor for operating power frequency voltages. It should behave as a short circuit for transient overvoltages of impulse character, discharge the heavy current, and recover its insulation without allowing the follow-up of the power frequency current.

<table>
<thead>
<tr>
<th>Surge Diverter Voltage and Current Ratings</th>
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<tr>
<td><strong>Diverter class</strong></td>
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Tests on Surge Diverters

(i) Power Frequency Sparkover Test
This is routine test. The test is conducted using a series resistance to limit the current in case a sparkover occurs. The arrester has to withstand at least 1.5 times the rated value of the voltage for five successive applications. The test is generally done also under dry and wet conditions.

(ii) Hundred per cent Standard Impulse Sparkover Test

This test is conducted to ensure that the diverter operates positively when overvoltages of impulse nature occur. The impulse generator is adjusted to give the standard impulse voltage of a preset magnitude specified in the specifications. The arrester has to sparkover every time in each of the ten successive applications. The test is done with both positive and negative polarity waveforms. Sometimes, the test is done by starting at a voltage level that does not give flashover at all, and is repeated in increasing steps of voltage till hundred per cent flashover occurs. The magnitude of the voltage at which hundred per cent flashover occurs is the required sparkover voltage.

(iii) Front of Wave Sparkover Test

In order to ensure that the surge diverter flashes over for very steep fronted waves of high peaks, this test is conducted using an overvoltage having a rate of rise of 100 kV/ps, per 12 kV of the rating. The estimated maximum steepness of the waves are specified in standards and specifications. The test is done by conducting hundred percent sparkover voltage test for increasing magnitudes of the standard impulse wave. The time to sparkover is measured. The volt-time characteristic of the diverter is plotted, and the intersection of the V-I characteristic and the line with slope of the virtual steepness of the front gives the front of a wave sparkover voltage.

(iv) Residual Voltage Test

This test is conducted on pro-rated diverters of ratings in the range 3 to 12 kV only. The voltage developed across the Non-Linear Resistor units (NLR) during the flow of surge currents through the arrester is-called the 'residual voltage. A pro-rated arrester is a complete, suitably housed section of an arrester including series gaps and non-linear series resistors in the same proportion as in the complete arrester.) Standard impulse currents of the rated magnitudes are applied, and the voltage developed across the diverter is recorded using a suitable voltage divider and a CRO. The magnitudes of the currents are approximately 0.5, 1.0, and 2.0 times the rated currents. From the oscillogram, a graph is drawn between the...
current magnitudes and the voltage developed across the diverter pro-rated unit. From the graph, the residual voltage corresponding to the exact rated current is obtained.

Let \( V_1 \) = rating of the complete unit,

\( V_2 \) = rating of the pro-rated unit tested,

\( V_{R1} \) = residual voltage of the complete unit, and

\( V_{R2} \) = residual voltage of the pro-rated unit.

Then, it is assumed that

\[
\frac{V_1}{V_2} = \frac{V_{R1}}{V_{R2}}
\]

Let VRM be the maximum permissible residual voltage for the complete unit. The ratio \( \frac{VRM}{V_1} = r \), is defined as a multiplying factor of the rating for the residual voltage test, which depends on \( V_1 \). The "diverter" is said to pass the test, if \( V_{R2} < rV \)

**Other Tests**

The other tests that are normally conducted on surge diverters are

(i) mechanical tests like porosity test, temperature cycle tests, and others,

(ii) pressure relief test,

(iii) the voltage withstand test on the insulator housing of the diverter,

(iv) the switching surge flashover test, and

(v) the pollution tests.

These tests are usually done on diverters used on Extra High Voltage (EHV) systems.