NOTE: PLEAS REFER CLASS NOTES ALSO FOR UNIT ONE AND UNIT THREE

UNIT THREE

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.

1 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

1.1 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

Energy stored $W = ½ C V^2$ so that change $d W = ½ V^2 d C = F d x$

Force $F=½ V^2 (dC/dx)$ Newton$=1/2 A\epsilon(V^2/x^2)$.

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

1.2Sphere 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 $\delta = 0.386P/(273+t)$

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 (figure 6.2) 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 (figure 6.3) 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 follows. $d < 0.5$ D, accuracy = ± 3 %; 0.75 D > d > 0.5 D, accuracy = ± 5 %

For accurate measurement purposes, gap distances in excess of 0.75D are not used.

The breakdown voltage characteristic is also dependant 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. + ½ V and - ½ V), as in a symmetrical gap, then the polarity has no effect. Figure 6.4 shows these breakdown voltage variations. 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.

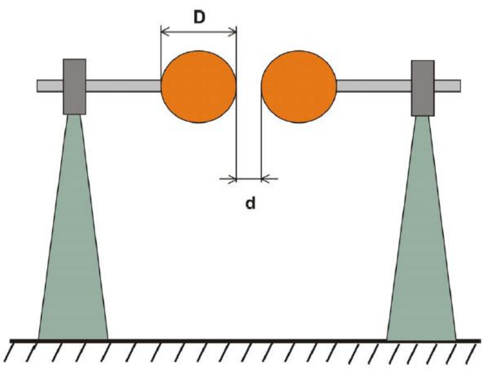
In sphere gaps used in measurement, to obtain high accuracy, the minimum clearance to be maintained between the spheres and the neighbouring bodies and the diameter of shafts are also specified, since these also affect the accuracy (figure 6.5). There is also a tolerance specified for the radius of curvature 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).

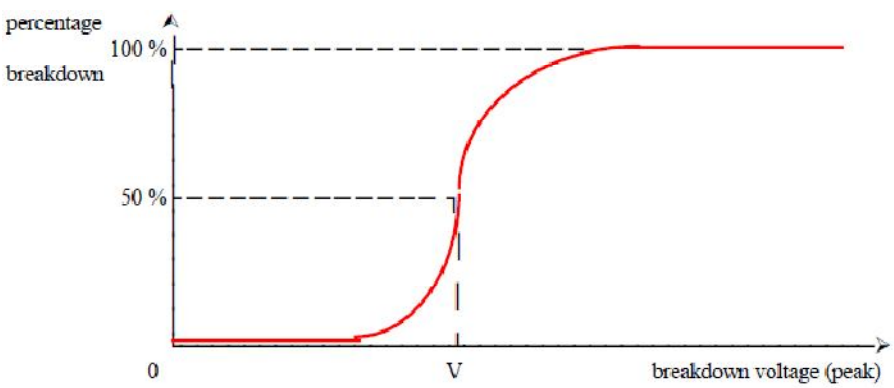
When spark gaps are to be calibrated using a standard sphere gap, the two gaps should not be connected in parallel. Equivalent spacing should be determined by comparing each gap in turn with a suitable indicating instrument.

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 (figure 6.6).





The factors that are influencing the peak voltage measurement using sphere gap are (i)Nearby earthed objects (ii)Atmosphere conditions (iii)Influence of humidity (iii)Irradiation (iv)Polarity and rise time of voltage waveform (v)Switching surge

1.3 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. The principle of operation is explained with the help of Fig. 4.8. *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 field lines are shown in Fig. 1. The electric field density σ is also shown. If electrode *M* is fixed and the voltage *V* is changed, the field density σ would change and thus a current *i* (*t*) would flow between *P* and the ground.

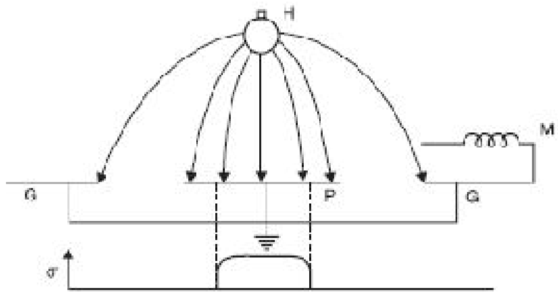


Fig. 1 Principle of generating voltmeter

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 $q(t)=C(t)V(t)$

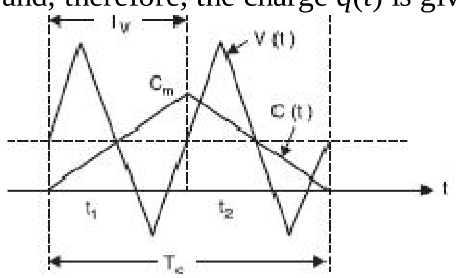


Fig. 2 Capacitance and voltage variation

Differentiating with respect to t gives $i(t)=dq/dt= V(dC/dt)$ for DC voltage application.

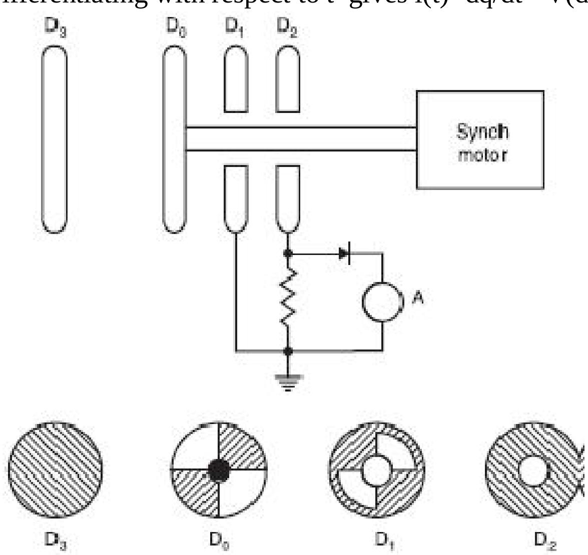


Fig. 3 schematic diagram of a generating voltmeter

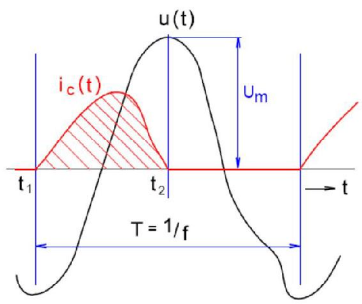
GVM shown in Fig 3 which employs rotating vanes for variation of capacitance. The high voltage electrode is connected to a disc electrode D_3 which is kept at a fixed distance on the axis of the other low voltage electrodes D_2, D_1, and D_0. The rotor D_0 is driven at a constant speed by a synchronous motor at a suitable speed. The rotor vanes of D_0 cause periodic change in capacitance between the insulated disc D_2 and the high voltage electrode D_3. The number and shape of vanes are so designed that a suitable variation of capacitance (sinusodial 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.

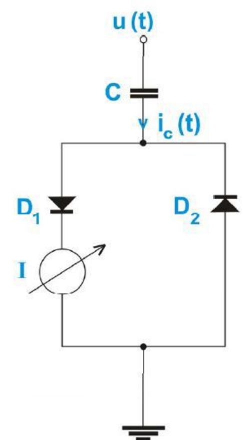
Advantages of generating Volmeter: (i) Scale is linear and extension of voltage range is easy (ii) Source loading is zero (iii) It can measure wide range of voltages (iv) There is no connection to H.V.electrode.

Disadvantage: (i) need calibration (ii) Careful construction is needed (iii*)* Disturbance in position and mounting of the electrodes make the calibration invalid.

2 THE CHUBB-FORTESCUE METHOD (for peak Ac HV measurement)

Simple and accurate method for the peak measurement of a.c. voltages.





Current through capacitor C:

$$i_C = C\frac{du}{dt}$$

Mean value of measured current:

$$I = \frac{1}{T}\int_{t_1}^{t_2} i_C dt = \frac{C}{T}[u(t_2) - u(t_1)] = \frac{C}{T}U_{pp}$$

Peak value of measured voltage:

$$U_m = \frac{I}{2Cf}$$

3 Voltage dividers

Voltages dividers for a.c., d.c. or impulse voltages may consist of resistors or capacitors or a convenient combination of these elements. Inductors are normally not used as voltage dividing elements as pure inductances of proper magnitudes without stray capacitance cannot be built and also these inductances would otherwise form oscillatory circuit with the inherent capacitance of the test object and this may lead to inaccuracy in measurement and high voltages in the measuring circuit. The height of a voltage divider depends upon the flash over voltage and this follows from the rated maximum voltage applied.

Now, the potential distribution may not be uniform and hence the height also depends upon the design of the high voltage electrode, the top electrode. For voltages in the megavolt range, the height of the divider becomes large. As a thumb rule following clearances between top electrode and ground may be assumed.

2.5 to 3 metres/MV for d.c. voltages.

2 to 2.5 m/MV for lightning impulse voltages.

More than 5 m/MV rms for a.c. voltages.

More than 4 m/MV for switching impulse voltage.

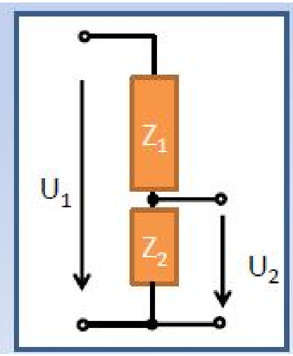
The divider dimensions are related to maximal applied voltage. The potential divider is most simply represented by two impedances Z_1 and Z_2 connected in series and the sample voltage required for measurement is taken from across Z_2,

Divider ratio:

$$\frac{U_2}{U_1} = \frac{Z_2}{Z_1 + Z_2}$$

Resistive divider $\quad \frac{U_2}{U_1} = \frac{R_2}{R_1+R_2}$

Capacitive divider $\quad \frac{U_2}{U_1} = \frac{C_1}{C_1+C_2}$



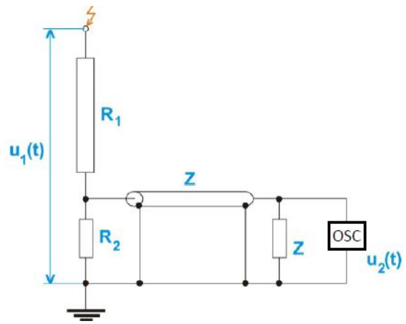
The voltage V_2 is normally only a few hundred volts and hence the value of Z_2 is so chosen that V_2 across it gives sufficient deflection on a CRO. Therefore, most of the voltage drop is available across the impedance Z_1 and since the voltage to be measured is in megavolt the length of Z_1 is large which result in inaccurate measurements because of the stray capacitances associated with long length voltage dividers (especially with impulse voltage measurements) unless special precautions are taken. On the low voltage side of the potential dividers where a screened cable of finite length has to be employed for connection to the oscillograph other errors and distortion of wave shape can also occur.

4 Resistive Dividers

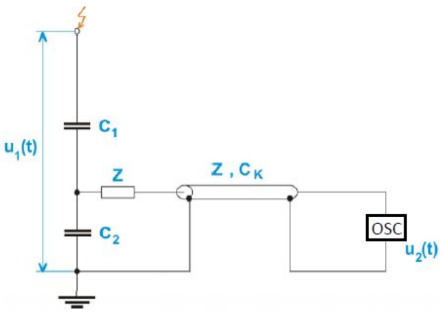
The resistance potential dividers are the first to appear because of their simplicity of construction, less space requirements, less weight and easy portability. These can be placed near the test object which might not always be confined to one location.

The length of the divider depends upon two or three factors. The maximum voltage to be measured is the first and if height is a limitation, the length can be based on a surface flash over gradient in the order of 3–4 kV/cm irrespective of whether the resistance R_1 is of liquid or wirewound construction. The length also depends upon the resistance value but this is implicitly bound up with the stray capacitance of the resistance column, the product of the two (RC) giving a time constant the value of which must not exceed the duration of the wave front it is required to record.

It is to be noted with caution that the resistance of the potential divider should be matched to the equivalent resistance of a given generator to obtain a given wave shape.

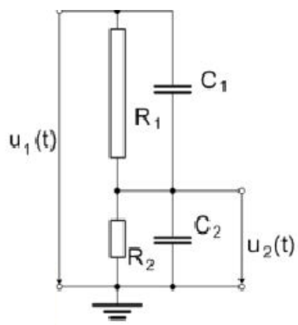


Capacitive Dividers



Capacitance potential dividers are more complex than the resistance type. For measurement of impulse voltages not exceeding 1 MV capacitance dividers can be both portable and transportable. In general, for measurement of 1 MV and over, the capacitance divider is a laboratory fixture. The capacitance dividers are usually made of capacitor units mounted one above the other and bolted together. It is this failure which makes the small dividers portable. A screening box similar to that described earlier can be used for housing both the low voltage capacitor unit C_2 and the matching resistor if required. The low voltage capacitor C_2 should be non-inductive. A form of capacitor which has given excellent results is of mica and tin foil plate, construction, each foil having connecting tags coming out at opposite corners. This ensures that the current cannot pass from the high voltage circuit to the delay cable without actually going through the foil electrodes. It is also important that the coupling between the high and low voltage arms of the divider be purely capacitive. Hence, the low voltage arm should contain one capacitor only; two or more capacitors in parallel must be avoided because of appreciable inductance that would thus be introduced. Further, the tappings to the delay cable must be taken off as close as possible to the terminals of C_2.

5. RC Voltage Divider



$$Z_1 = \frac{R_1}{1 + j\omega C_1 R_1} \qquad Z_2 = \frac{R_2}{1 + j\omega C_2 R_2}$$

$$\frac{U_2}{U_1} = \frac{\omega C_1 R_1 - jR_2}{\omega R_1 R_2 (C_1 + C_2) - j(R_1 + R_2)}$$

$$Im\left(\frac{U_2}{U_1}\right) = \frac{\omega R_1 R_2 (C_1 R_1 - C_2 R_2)}{(R_1 + R_2)^2 + \omega^2 R_1^2 R_2^2\,(C_1 + C_2)^2} = 0$$

$$\Rightarrow C_1 R_1 = C_2 R_2$$

6 MEASUREMENT OF HIGH D.C., AND IMPULSE CURRENTS

High currents are used in power system for testing circuit breakers, cables lightning arresters etc. and high currents are encountered during lightning discharges, switching transients and shunt faults. These currents require special techniques for their measurements.

6.1 High Direct Currents

Low resistance shunts are used for measurement of these currents. The voltage drop across the shunt resistance is measured with the help of a milli-voltmeter. The value of the resistance varies usually between 10 microohm and 13 milliohm. This depends upon the heating effect and the loading permitted in the circuit. The voltage drop is limited to a few millivolts usually less than 1 V. These resistances are oil immersed and are made as three or four terminal resistances to provide separate terminals for voltage measurement for better accuracy.

6.2 Hall Generators

Hall effect is used to measure very high direct current. Whenever electric current flows through a metal plate placed in a magnetic field perpendicular to it, Lorenz force will deflect the electrons in the metal structure in a direction perpendicular to the direction of both the magnetic field and the flow of current. The charge displacement results in an e.m.f. in the perpendicular direction called the Hall voltage. The Hall voltage is proportional to the current I, the magnetic flux density B and inversely proportional to the plate thickness d *i.e.,* $V_H = RBI/d$

where R is the Hall coefficient which depends upon the material of the plate and temperature of the plate. For metals the Hall coefficient is very small and hence semiconductor materials are used for which the Hall coefficient is high.

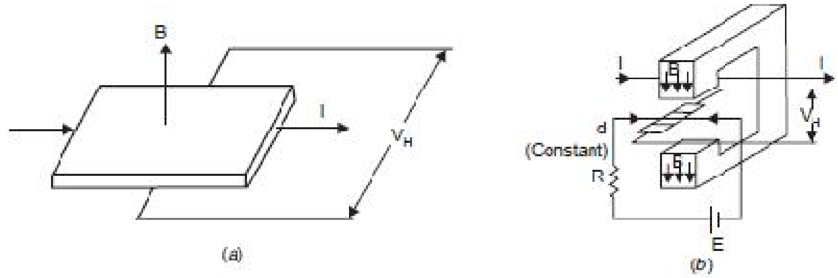


Fig. Hall generator

When large d.c. currents are to be measured the current carrying conductor is passed through an iron cored magnetic circuit (Fig. (*b*)). The magnetic field intensity produced by the conductor in the air gap at a depth d is given by $H = 1/(2\pi d)$
The Hall element is placed in the air gap and a small constant d.c. current is passed through the element. The voltage developed across the Hall element is measured and by using the expression for Hall voltage the flux density B is calculated and hence the value of current I is obtained.

6.3 High Power Frequency Currents

High Power frequency currents are normally measured using current transformers as use of low resistance shunts involves unnecessary power loss. Besides, the current transformers provide isolation from high voltage circuits and thus it is safer to work on *HV* circuits Fig. below shows a scheme for current measurements using current transformers and electro-optical technique.

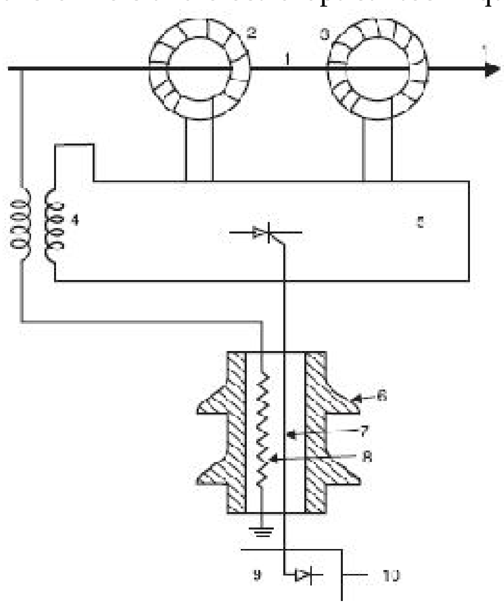
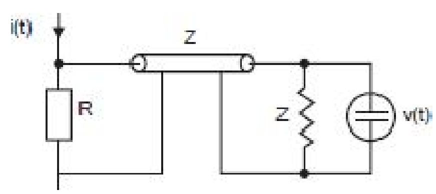


Fig. Current transformers and electro-optical system for high a.c. current measurements
A voltage signal proportional to the current to be measured is produced and is transmitted to the ground through the electro-optical device. Light pulses proportional to the voltage signal are transmitted by a glass optical fibre bundle to a photodetector and converted

back into an analog voltage signal. The required power for the signal convertor and optical device are obtained from suitable current and voltage transformers.

6.4 High Frequency and Impulse Currents

In power system the amplitude of currents may vary between a few amperes to a few hundred kiloamperes and the rate of rise of currents can be as high as 10^{10} *A*/sec and the rise time can vary between a few micro seconds to a few macro seconds. Therefore, the device to be used for measuring such currents should be capable of having a good frequency response over a very wide frequency band. The methods normally employed are—(*i*) resistive shunts; (*ii*) elements using induction effects; (*iii*) Faraday and Hall effect devices. With these methods the accuracy of measurement varies between 1 to 10%. Fig. shows the circuit diagram of the most commonly used method for high impulse current measurement. The voltage across the shunt resistance *R* due to impulse current *i*(*t*) is fed to the oscilloscope through a delay cable *D*. The delay cable is terminated through an impedance *Z* equal to the surge impedance of the cable to avoid reflection of the voltage to be measured and thus true measurement of the voltage is obtained. Since the dimension of the resistive element is large, it will have residual inductance *L* and stray capacitance *C*. The inductance could be neglected at low frequencies but at higher frequencies the inductive reactance would be comparable with the resistance of the shunt. The effect of inductance and capacitance above 1 MHz usually should be considered. The resistance values range between 10 micro ohm to a few milliohms and the voltage drop is of the order of few volts. The resistive shunts used for measurements of impulse currents of large duration is achieved only at considerable expense for thermal reasons. The resistive shunts for impulse current of short duration can be built with rise time of a few nano seconds of magnitude. The resistance element can be made of parallel carbon film resistors or low inductance wire resistors of parallel resistance wires or resistance foils.



Assuming the stray capacitance to be negligibly small the voltage drop across the shunt in complex frequency domain may be written as $V(s) = I(s)[R + Ls]$

It is to be noted that in order to have flat frequency response of the resistive element the stray inductance and capacitance associated with the element must be made as small as possible. In order to minimise the stray field effects following designs of the resistive elements have been suggested and used

1. Bifilar flat strip shunt.
2. Co-axial tube or Park's shunt
3. Co-axial squirrel cage shunt.

The bifilar flat strip shunts suffer from stray inductance associated with the resistance element and its potential leads are linked to a small part of the magnetic flux generated by the current that is being measured. In order to eliminate the problems associated with the bifilar shunts, coaxial shunts were developed. Here the current enters the inner cylinder of the shunt element and returns through an outer cylinder. The space between the two cylinders is occupied by air which acts like a perfacts insulator. The voltage drop across the element is measured between the potential pick up point and the outer case. The frequency response of this element is almost a flat characteristic upto about 1000 MHz and the response time is a few nanoseconds. The upper frequency limit is governed by the skin effect in the sensitive element.

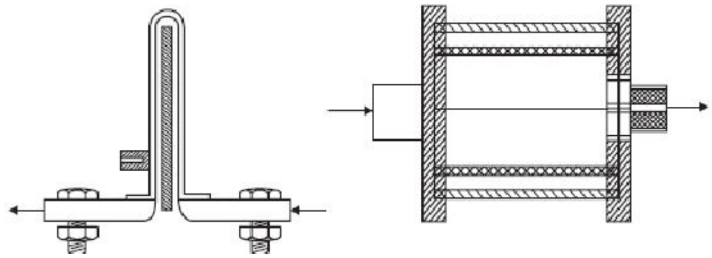


Fig. (i) Bifilar flat strip; (ii) Co-axial squirrel cage

Squirrel cage shunts are high ohmic shunts which can dissipate larger energies as compared to coaxial shunts which are unsuitable due to their limitation of heat dissipation, larger wall thickness and the skin effect. Squirrel cage shunt consists of thick metallic rods or strips placed around the periphery of a cylinder and the structure resembles the rotor construction of a double squirrel cage induction motor. The step response of the element is peaky and, therefore, a compensating network is used in conjunction with the element to improve its frequency response. Rise times less than 8 *n* sec and band width of 400 MHz have been obtained with these shunts.

6.5 Elements using Induction Effects(Rogowski coil)

If the current to be measured is flowing through a conductor which is surrounded by a coil as shown in Fig., and M is the mutual inductance between the coil and the conductor, the voltage across the coil terminals will be: $v(t) = M(di/dt)$

Usually the coil is wound on a non-magnetic former in the form of a toroid and has a large number of turns, to have sufficient voltage induced which could be recorded. The coil is wound criss-cross to reduce the leakage inductance. If N is the number of turns of the coil, A the coil area and lm its mean length, the mutual inductance is given by

$$M = \mu_0 NA/lm$$

Usually an integrating circuit RC is employed as shown in Fig. to obtain the output voltage proportional to the current to be measured. The output voltage is given by $v_0(t) = Mi(t)/(RC)$

Integration of $v(t)$ can be carried out more elegantly by using an appropriately wired operational amplifier. The frequency response of the Rogowski coil is flat upto 100 MHz but beyond that it is affected by the stray electric and magnetic fields and also by the skin effect.

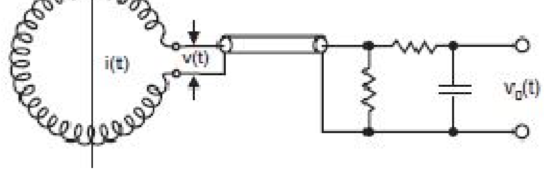


Fig. Rogowski coil for high impulse current measurements

6.6 Magnetic Links

These are used for the measurement of peak magnitude of the current flowing in a conductor. These links consist of a small number of short steel strips on high retentivity. The link is mounted at a known distance from the current carrying conductor. It has been found through experiments that the remanant magnetism of the link after impulse current of 0.5/5 micro sec shape passes through the conductor is same as that caused by a direct current of the same peak value. Measurement of the remanance possessed by the link after the impulse current has passed through the conductor enables to calculate the peak value of the current. For accurate measurements, it is usual to mount two or more links at different distances from the same conductor. Because of its relative simplicity, the method has been used for measurement of lightning current especially on transmission towers.

It is to be noted that the magnetic links help in recording the peak value of the impulse current but gives no information regarding the wave shape of the current. For this purpose, an instrument called Fulcronograph has been developed which consists of an aluminium wheel round the rim of which are slots containing magnetic links of sufficient length to project on both sides of the wheel. As the wheel is rotated, the links pass successively through a pair of narrow coils through which flows the current to be measured. The current at the instant during which a particular link traverses the coil, can be determined by a subsequent measurement of the residual flux in the link and, therefore, a curve relating the variation of current with time can be obtained. The time scale is governed by the speed of rotation of the wheel.

Hall Generators

The high amplitude a.c. and impulse currents can be measured by Hall Generator described earlier. For the Hall Generator, though a constant control current flows which is permeated by the magnetic field of the current to be measured, the Hall voltage is directly proportional to the measuring current. This method became popular with the development of semi-conductor with sufficient high value of Hall constant. The band width of such devices is found to be about 50 MHz with suitable compensating devices and feedback.