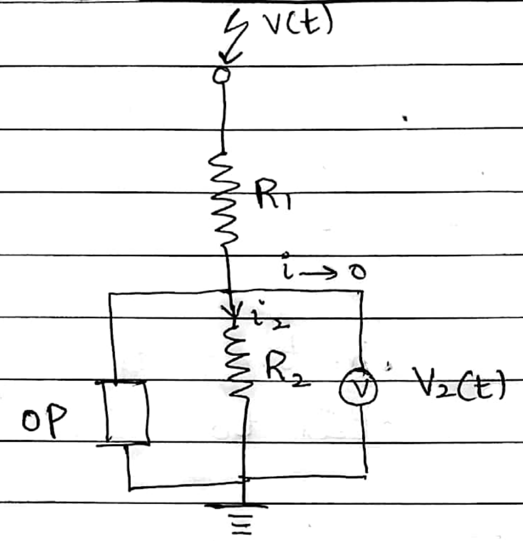
Measurement of High Voltages

Measurement of high voltages (dc, Ac or impulse) involves unusual problems that may not be encountered in common electrical measurements. The problems increase with the voltage but are still easy to solve for voltages of some 10 kV only & become difficult if 100s of kV or megavolts have to be measured. The difficulties are mainly related to Large structures. necessary to control the electric fields. The measurement methods for voltages applied for testing of HV equipments or in research are different from those used within the electric power transmission system.

1) High ohmic resistor in series with an ammeter
2) High ohmic resistive voltage divider.

2) High ohmic Resistive Voltage Divider



This method consists of measuring voltage across a low ohmic resistor R_2 in series with a high ohmic resistor R_1. High voltage is given by

$$V(t) = V_2(t)\left(1 + \frac{R_1}{R_2}\right) \quad — (1)$$

Measurement uncertainty now depends on ratio of R_1 to R_2. As both resistors carry the same current, the influence of voltage and temperature coefficients of resistors can be eliminated to a large extent if both resistors employ the same resistor technology, are subjected to uniform field stresses and if provisions are made to prevent accumulation of heat within any section of the resistor column. Thus, the uncertainty of the measurement can be greatly reduced.

The time variation of the voltage V(t) can also be measured if the output $V_2(t)$ is connected to a CRO. However, the frequency dependency of the transfer characteristic due to stray inductances and capacitances cannot be avoided.

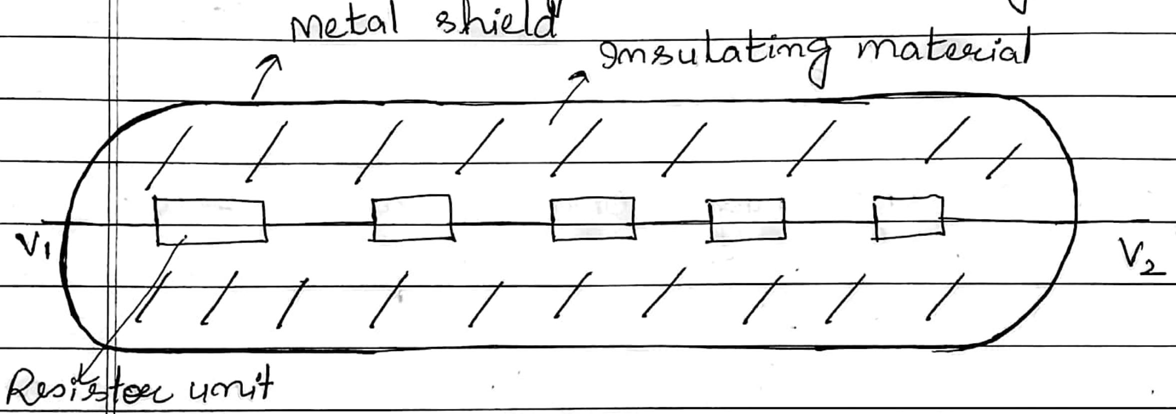
Date :- 10-04-19

Resistor technology for High Voltage Resistors

In practice, the high ohmic resistor used for measuring high voltages is composed of a large no. of individual elements connected in series and no single units are commercially available. Wire wound metal resistors made from Cu-Mn, Cu-Ni, & Ni-Cr alloys or similar compositions have very low temperature coefficients, down to about $10^{-5}/k$ and have adequate accuracy. However, the specific resistance of these materials is not very high and therefore the length of the wire required becomes very considerable even for currents of 1 milliampere and for the finest gauge which can be made.

Especially for voltage dividing systems, common carbon composition or metal oxide filled resistors are preferably used. They should be carefully selected as they have high values of temperature coefficients & voltage coefficients. The self inductance of such resistors is negligible.

Since individual resistor units are made for a voltage of about 1kV. Large no. of such units are connected in series. The resistor units are grouped to form resistor elements Each element having many units placed within small cylindrical housings.

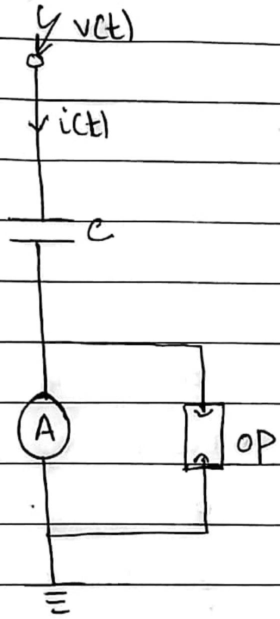


Resistor Element for HV resistor

Metal shields are provided at the two ends to prevent too high electric field gradings. The resistor elements are arranged in a helix on an insulating support to form a cylinder of large diameter across which the potential continuously decreases from top to bottom. The HV end of resistor is usually fitted with a large stress ring which again prevents concentration of electric field over the height of the resistor

For voltages higher than about 100kV, air insulated design becomes difficult. The resistor is then placed in an insulating vessel filled with mineral oil or highly insulating gases.

Ammeter in Series with a High Voltage Capacitor



→ It is used for measuring AC
→ Ammeter should be an AC ammeter so it is an rms indicating instrument.

Measured current for pure sinusoidal voltage would be $I = \omega C V$ — (1)

$$V = \frac{I}{\omega C} \quad — (2)$$

If the input voltage v(t) has harmonics, then effective voltage will be given by.

$$V_{eff} = \sqrt{V_1^2 + V_2^2 + \dots + V_n^2} \quad — (3)$$

$V_1 \rightarrow I_1$

$V_2 \rightarrow I_2$

$I_1 = \omega C V_1$ — (4)

$I_2 = 2\omega C V_2$ — (5)

⋮

$I_n = n\omega C V_n$ — (6)

Current measured by the ammeter.

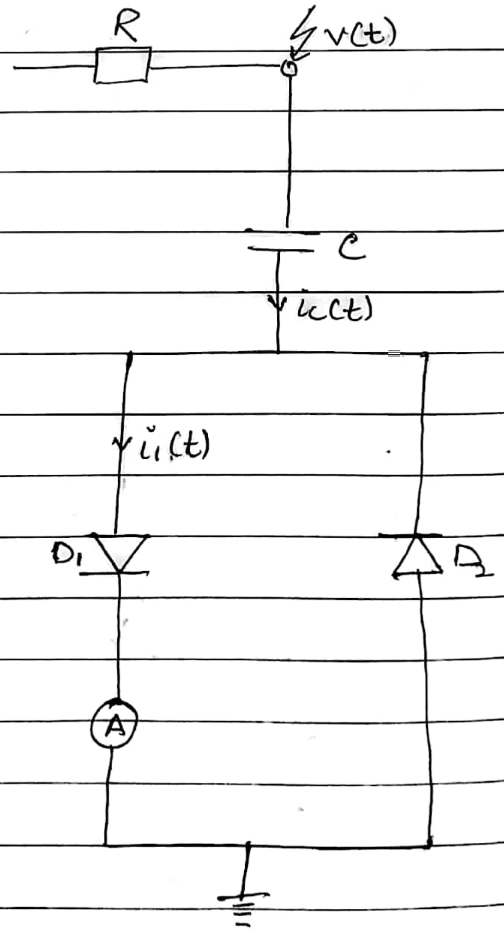
$$I_{eff} = \sqrt{I_1^2 + I_2^2 + \cdots + I_n^2}$$

$$I_{eff} = \omega C \sqrt{V_1^2 + 4V_2^2 + 9V_3^2 + \cdots + n^2 V_n^2}$$

$$\frac{I_{eff}}{\omega C} = \sqrt{V_1^2 + 4V_2^2 + \cdots + n^2 V_n^2}$$

Since this voltage is greater than V_{eff}, therefore this method cannot be used for Ac with harmonics so it is used for measuring a pure sinusoid.

Ac Peak measurement by Chubb-Fortescue method

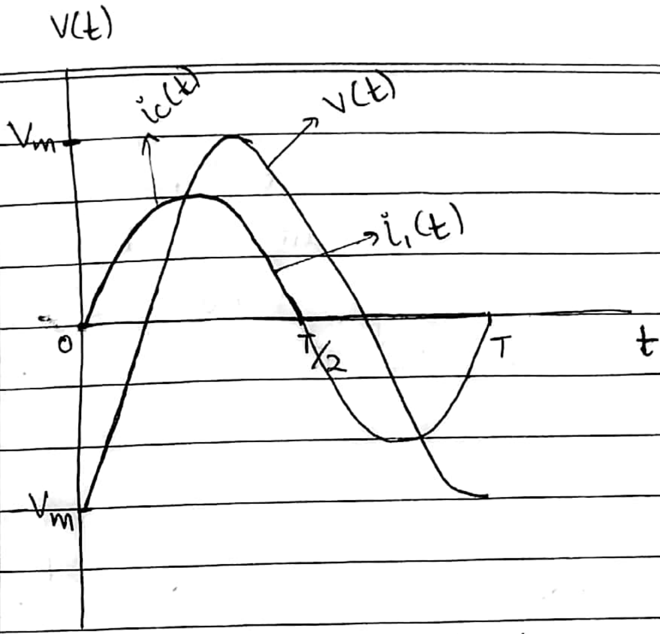


→ This method is simple & accurate.

C → standard pressurised gas Capacitor.

D_1, D_2 → 2 diodes connected in antiparallel.

A → Average indicating instrument.



Current measured by ammeter $I_1 = \frac{1}{T}\int_0^T i_1(t)\,dt$ —(1

$$I_1 = \frac{1}{T}\int_0^{T/2} i_c(t)\,dt$$

$$i_c(t) = C\frac{dv}{dt} \quad -(3)$$

$$C\,dv = i_c(t)\,dt$$

$$I_1 = \frac{1}{T}\int_{-V_m}^{V_m} C\,dv$$

$$I_1 = \frac{C}{T}\,V\Big|_{-V_m}^{V_m}$$

$$I_1 = \frac{C}{T}\,2V_m$$

$$I_1 = 2fC\,V_m \quad -(4)$$

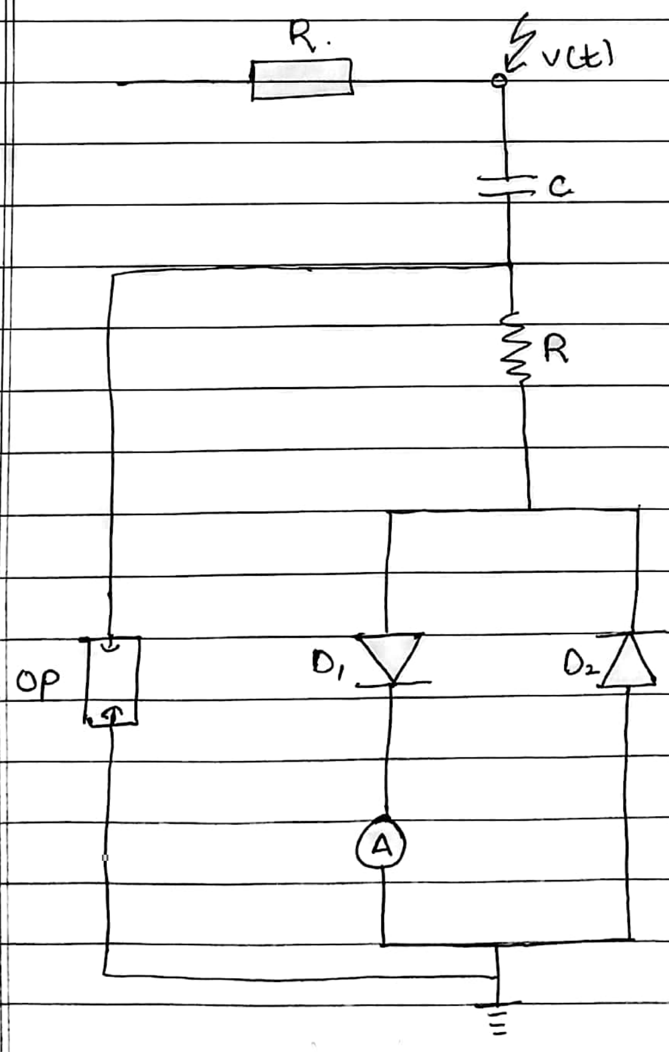
$$\boxed{V_m = \frac{I_1}{2fC}}$$

→ The accuracy of this method is 0.05%.
→ It can be used for Non-sinusoidal AC voltages also.

Under transient conditions, there might occur problem in this arrangement. The spikes or large transients may result in Large currents which may damage whole Circuit. Therefore damping resistor is used in the circuit.

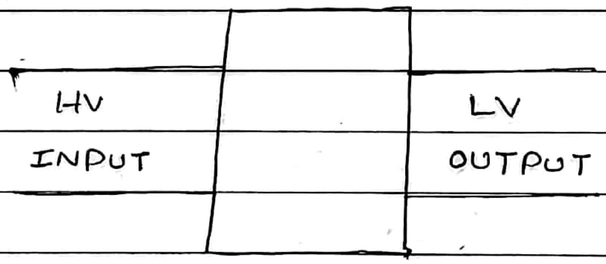
During breakdown, overvoltage may be produced therefore to protect whole arrangement, over protection is employed.

Over Voltage protection circuit



Voltage Dividing Systems

Voltage dividers provide a convenient method for the measurement of very high voltages. Proportional to the high voltage input, voltage dividers provide a low output which can be easily measured using low voltage measuring devices. The voltage waveforms can be displayed on common CROs, digital oscilloscopes and transient recorders which can be built to have very high bandwidth and can capture nearly every kind of short duration single phenomenon like impulse voltages.



The voltage dividers necessary to accomodate high voltages (which may have magnitude upto some mega volts) are specialised apparat and it is not easy to manufacture these with adequate accuracy. The application of voltage dividers involves many complications due to the complex interactions present in the voltage dividing circuits.

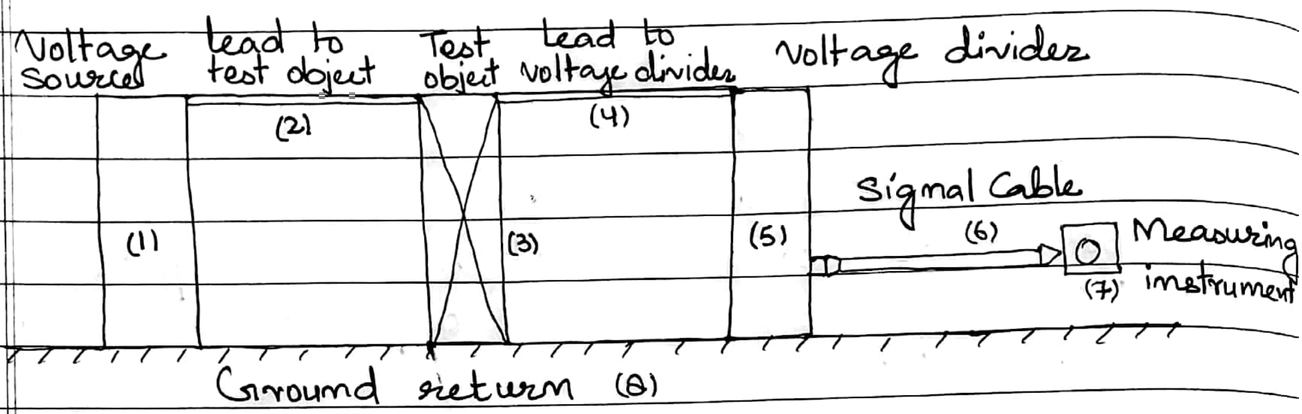


Fig 1

Fig 1. shows a typical layout showing the use of a voltage dividing system. The lead (2) to the test object may include an impedance or a resistance to damp oscillations or to limit the short circuit currents if the test object fails.

The voltage dividers are electromagnetically exposed networks and cannot be shielded against external fields. All the objects in the vicinity of the divider will disturb the field distribution and thus the divider performance. The voltage dividers are therefore placed away from any energised objects. The Lead (4) from the test object to the voltage divider is therefore an integral part of measuring system. A damping resistor at the input end of this lead contribute to transfer characteristics of the system.

In order to avoid heavy electromagnetic interactions between the recorded instrument and the HV test area as well as safety hazards, the length of the signal cable must be adequate. The appropriate ground return (s) should assume no significant voltage drops for even highly transient phenomenon and keep the ground potential to earth as closely as possible. To reduce the impedance of ground return, large metallic sheats of highly conductive material such as cu, Al are best.

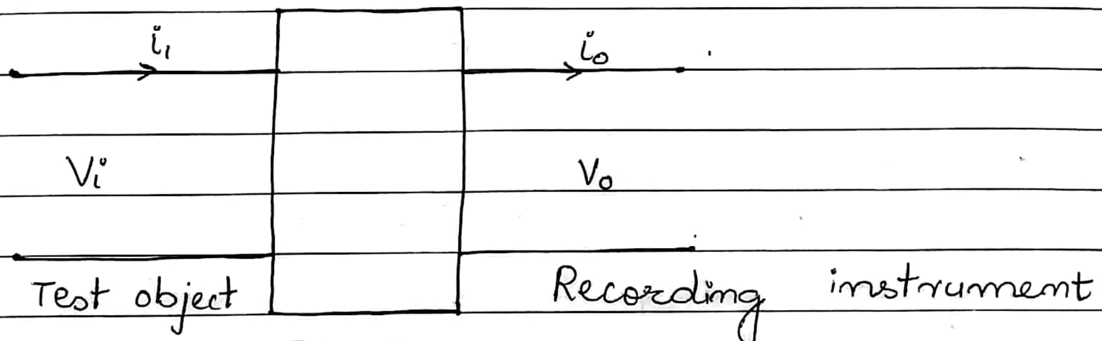
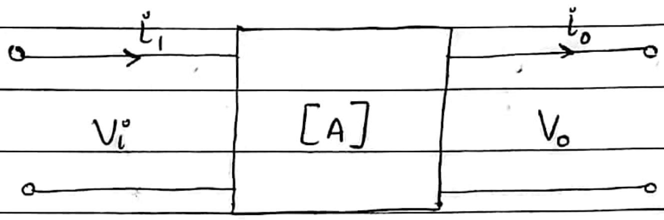


Fig. 2

The voltage measuring system is a four terminal network & can be represented as shown in fig 2.

V_i indicates the voltage across the test object and V_o appears at the recording instrument. The input voltage V_i is either continuous steady state voltage for dc or Ac generating systems or single - events for impulse voltages. In both cases the instantaneous value will change with time even for dc voltages with a periodic ripple.

Transfer Characteristics of voltage Dividing System



For a sinusoidal input

$$V_i = V_{mi} \sin(\omega t + \phi_i)$$

output,

$$V_o = V_{mo} \sin(\omega t + \phi_o)$$

$$\text{Amplitude response} = \frac{V_{mo}}{V_{mi}} = H(\omega)$$

$$\text{phase response} = \phi_o - \phi_i = \phi(\omega)$$

Neither dc voltages with ripple nor Ac test voltages are pure sinusoids but are periodic in nature.

The input voltages may be then described by superposition of a no. of sinusoids with discrete frequencies obtained by application of fourier Series. For every component with a frequency $\omega_K = K\omega$, the network response may easily be found and the responses can be summed up using the principle of superposition.

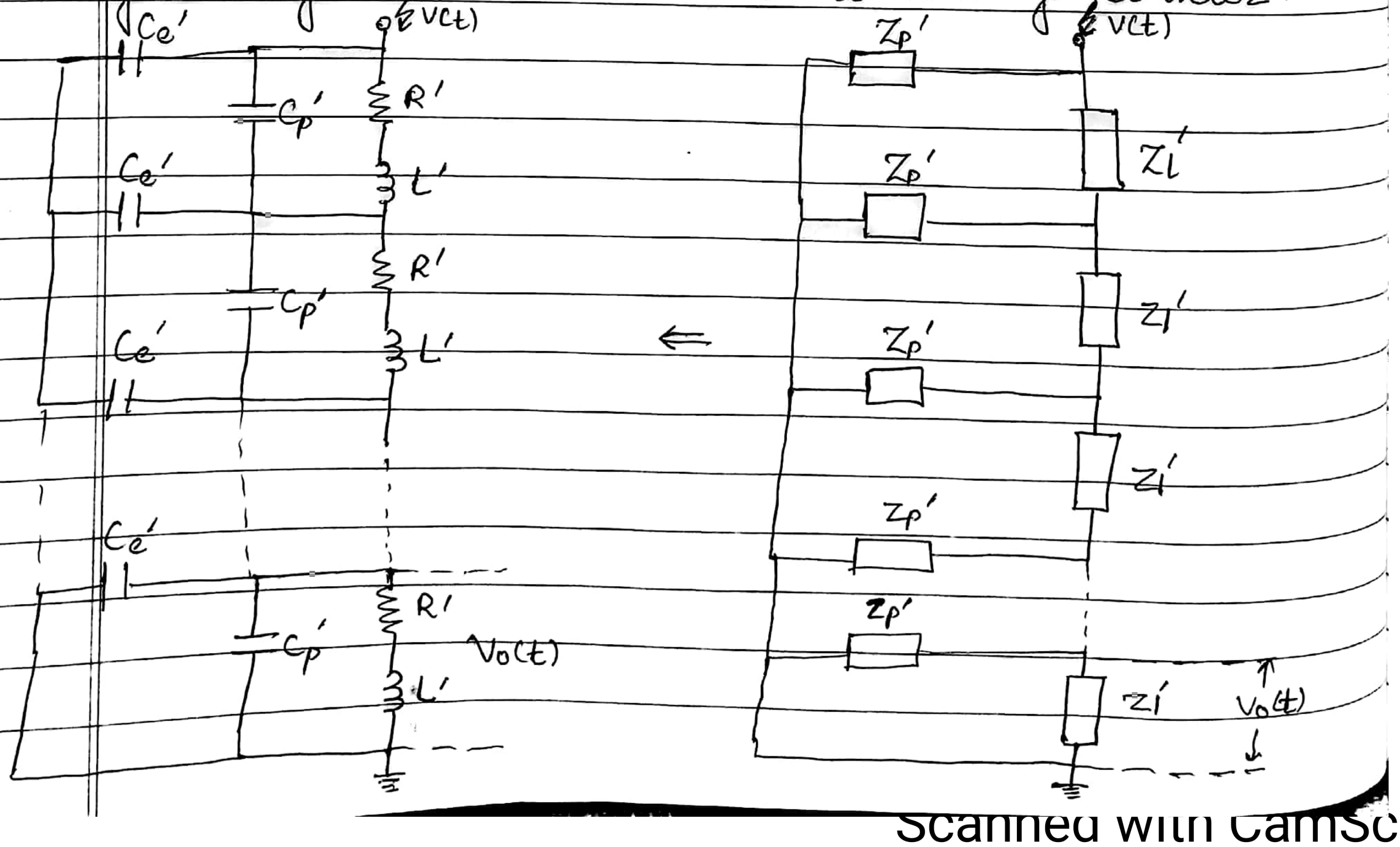
For single events of impulse voltages, the input voltage V_i can only be presented by a continuous frequency spectrum defined by a fourier integral or fourier transform.

The highest demands on the measuring transfer system are clearly imposed by impulse voltages. The amplitude spectrum for a full lightening impulse extends upto about 0.5 to 1 MHz. The amplitude response of the measuring system which is nearly flat upto this frequency wouldnot provide significant errors. Depending upon the decay of amplitude response, the bandwidth (-3 DB) has to be much higher i.e about 5 to 10 MHZ. The bandwidth required for a chopped impulse voltage will be much higher, which may not be achieved easily with measuring systems for very high voltages.

Types of Voltage Dividers

Voltage dividers for dc, Ac or impulse Voltages consist of resistors or Capacitors or Convenient combinations of these elements. Inductors are not generally used for measuring very high voltages. The elements of the voltage divider are usually installed within an insulating vessel of cylindrical shape. The height of the divider depends upon the potential distribution and flashover voltage. The design of the top electrode has a great influence on the potential distribution. The most difficult problem in simulation of a voltage divider is the adequate representation of the stray Capacitances.

A distributed parameter network with equally distributed parameters as shown in fig. is generally used to simulate a voltage divider.



i) Resistive Voltage Dividers

Resistive voltage dividers are ideal for the measurement of pure dc voltages for which

$$V_o(t) = \frac{R_2}{R_1 + R_2} V(t)$$

$R_1 = (n-1) R'$

$R_2 = R'$

$$V(t) = \left(1 + \frac{R_1}{R_2}\right) V_o(t)$$

The ability to measure Ac voltages and dc voltages with ripple depends upon the decre of the transfer function with frequency. The controlling factor is given by the product RC_e where

$$R = nR'$$

$$C_e = n C_e'$$

The bandwidth of the divider is given by

$$f_B = \frac{1.15}{RC_e}$$

(Hz) $R \rightarrow \Omega$

$C_e \rightarrow F$

Response time

$$T^o = \frac{RC_e}{6}$$

C_e (PF) $\approx (10 - 15) \times$ Height (m)

$R_{(G\Omega)} \approx (1 - 2) \times$ Voltage (MV)

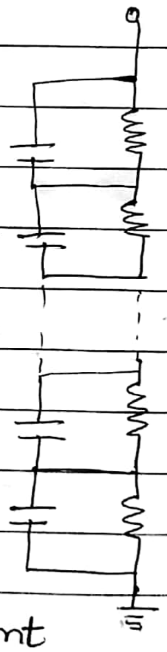
$$f_B = \frac{50 \text{ to } 150}{\text{Height} \times \text{voltage}}$$

(Hz) (m) (mv)

The measurement of power frequency voltage needs $f_B > 1$ KHZ resulting in a product height & voltage of about 100 kV m. This product limits the application of resistive voltage dividers to AC voltages not exceeding 100 to 200 kV and dc voltages with ripple to not exceeding some 100 kV.

Dated:- 30-04-19

Compensated Resistive voltage Divider



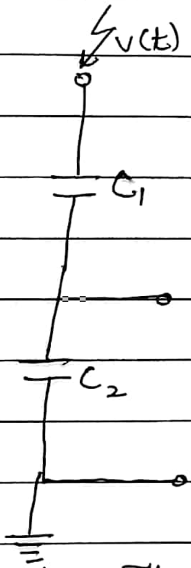
→ They are known as parallel mixed RC divider.

→ A parallel mixed RC divider is formed by connecting capacitor units in parallel with resistor units of a resistive voltage divider.

→ Compensation of high ohmic dividers commonly used for the measurement of DC or AC voltages is very attractive to increase the performance in the intermediate frequency range (100 Hz upto some 100 kHz). However, it is not recommended to use these dividers for measurement of high impulse voltages.

Capacitive Voltage Dividers (CVDs)

A pure Capacitive voltage divider Can be made either by using a single HV Capacitor unit i,e a compressed gas Capacitor in series with a low voltage Capacitor or by many series Connected Capacitor units to form the HV Capacitor.

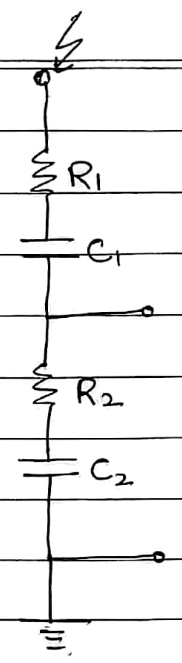


A Capacitive voltage divider within the whole measuring Circuits with leads Connected to its input will form a series RLC circuit.

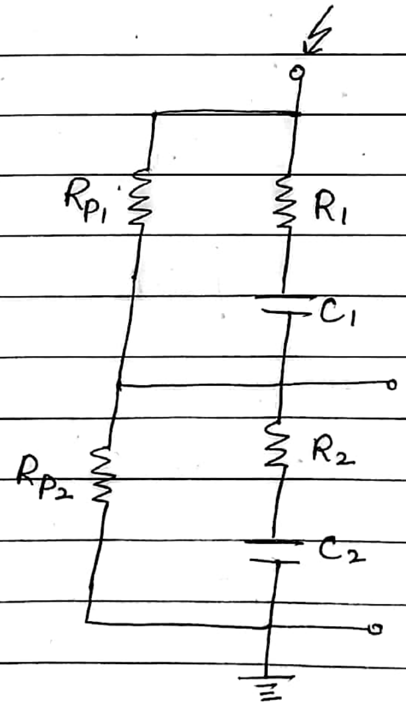
They are sensitive to input voltages having short rising times and this may Cause the output voltage to oscillate. Thus pure Capacitive voltage dividers are not adequate to measure impulse voltages.

Excellent transient performance Can be obtained by inserting resistor units, not too high in series with the Capacitors to damp the oscillations such a divider is Called series damped Capacitive voltage divider. The input impedance of these dividers increases with decreasing frequency and hence the loading effect of voltage source is Limited.

They Can therefore be applied for AC voltages, Lightning and switching impulse voltages with without any restrictions.



If a parallel branch of high ohmic resistor is added Dc voltages can also be measured and the resulting divider is called as "<u>Universal Divider</u>"



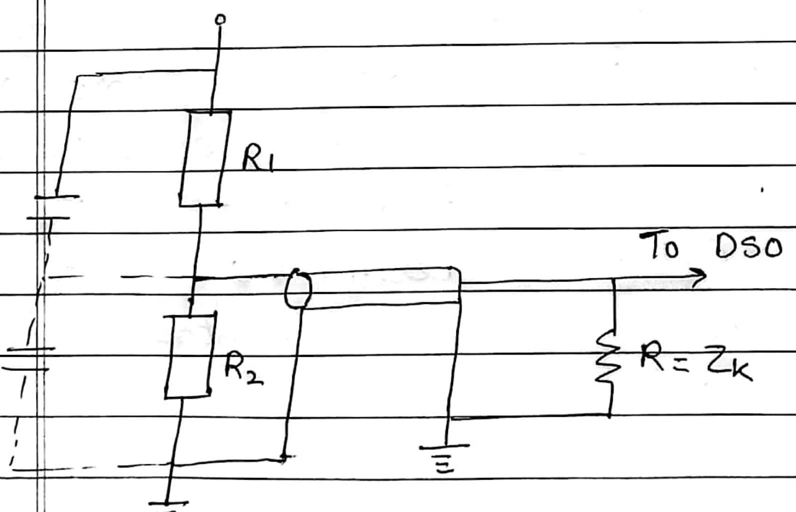
Signal Cable Matching For HV Dividers

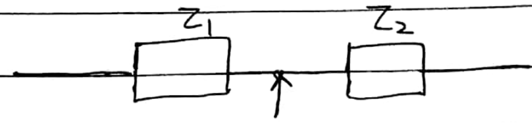
For accurate measurements using voltage dividers, it is essential that the impedance at signal cable terminals be matched with the signal cable impedances. The signal cable is treated as lossless line with a surge impedance of

$$Z_K = \sqrt{\frac{L_K}{C_K}} \quad \& \text{ a travel time } T_K = \sqrt{L_K C_K}$$

1) Signal Cable matching for Resistive voltage dividers

For resistive voltage dividers, the cable matching is simply done with the pure resistance $R = Z_K$ at the end of signal cable to avoid reflections at this end.





Reflection Coefficient $\rho_v = \frac{Z_2 - Z_1}{Z_2 + Z_1}$

$$\rho_v = \frac{1 - Z_1/Z_2}{1 + Z_1/Z_2}$$

The reflection coefficient becomes zero & the voltage across R_2 is undistortedly transmitted by the Cable.

The input impedance of the signal Cable Z_K appears in parallel with R_2 & forms an integral part of the dividers LVR (Low voltage resistor).

Usually $Z_K = 50 - 75\,\Omega$

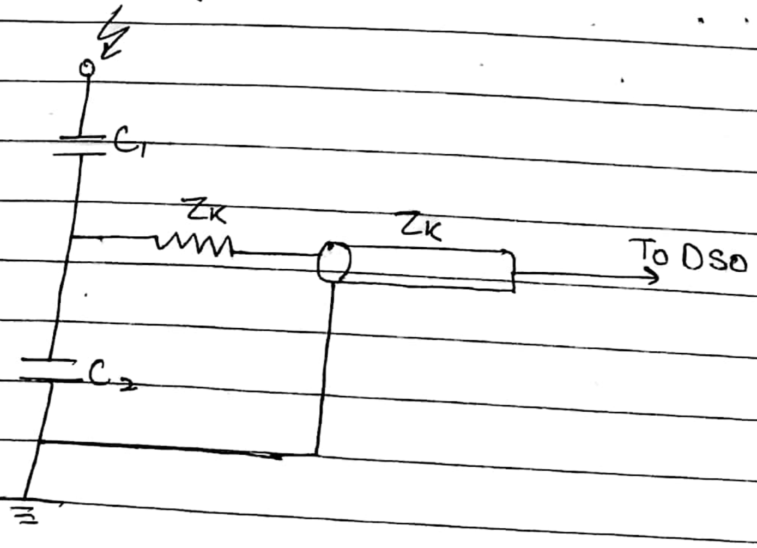
& $R_2' = (R_2 \parallel Z_K)$

2) For parallel mixed RVD

For parallel mixed RVD, the same procedure for matching applies.

3) For Capacitive Voltage Divider

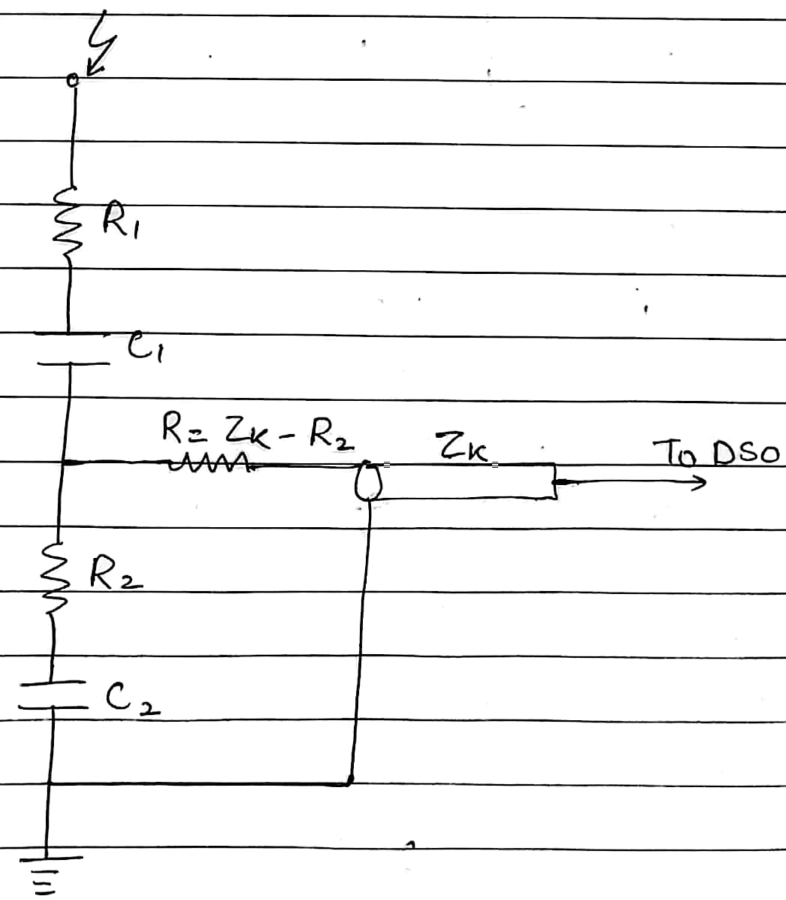
For Capacitive voltage dividers, the signal Cable Cannot be matched at its end, as a low ohmic resistor at the end would Load the LVR. To avoid travelling wave oscillations, the Cable is terminated at its input end by a series resistor with $R = Z_K$



Then a voltage step at C_2 will be halved by $R = Z_K$ at the Cable input end because R and Z_K will form a voltage divider. This halved voltage travells to the open end & is doubled by the reflection. Thus, the original amplitude of voltage across C_2 appears at the input of the recording instrument.

4) For Damped Capacitive Voltage Divider.

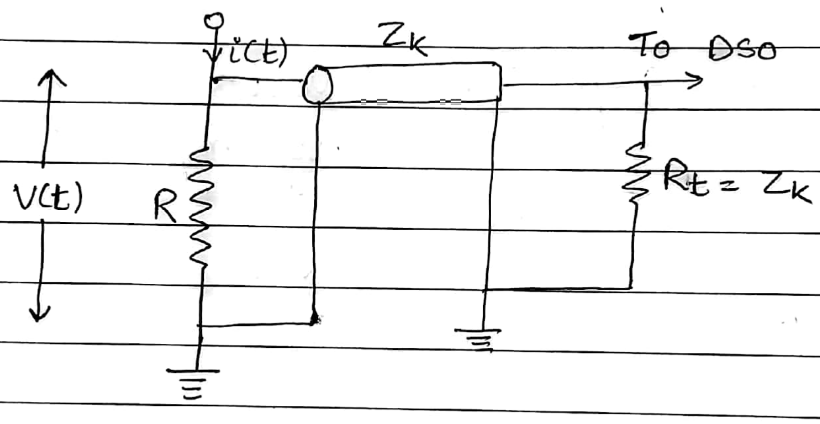
For damped Capacitive voltage divider, the matching impedance at the input end must be equal to $Z_K - R_2$.



Measurement of High Impulse Currents

1. Resistive shunts
2. Rogowoski Coils (Magnetic Potentiometers)
3. Magneto - optic Devices / Faraday Effect Devices.
4. Hall effect Transducers.

1. Resistive shunts :-

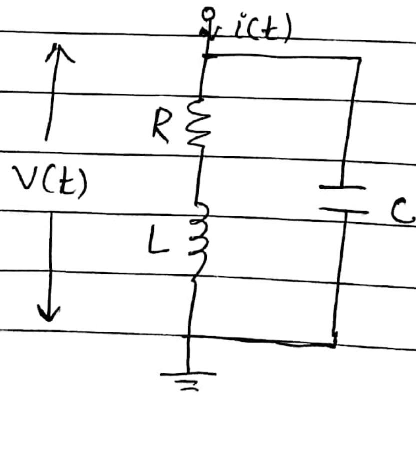


$$V(t) = i(t)\,R$$

$$i(t) = \frac{V(t)}{R}$$

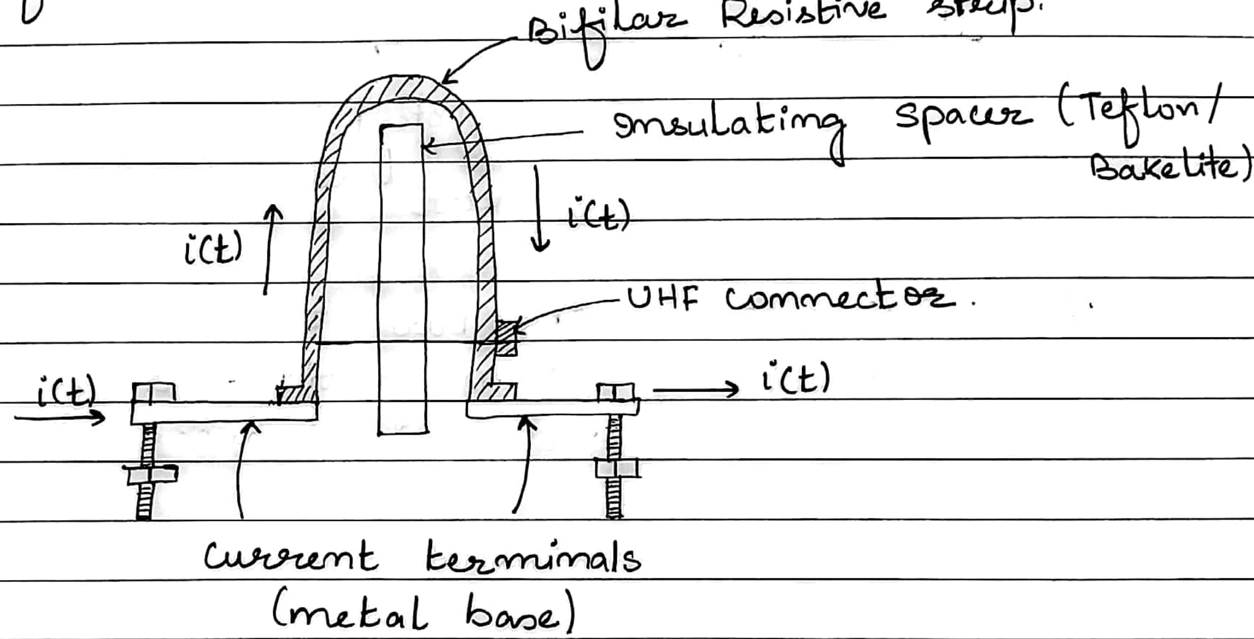
Value of resistance is small, ranges from a fraction of a mΩ to some 100mΩ

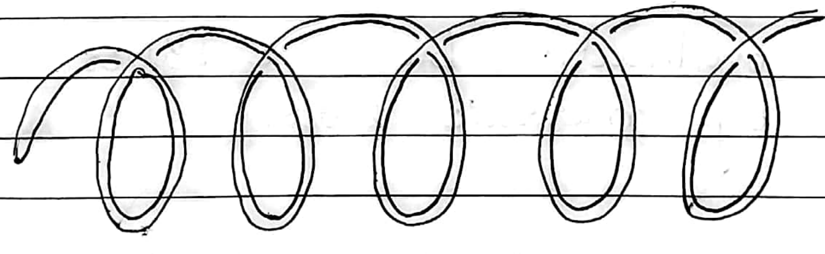
At high frequencies, the effect of stray L & C is high, but the effect of L is more dominant over C.



To reduce L, different types of constructions are employed for resistor.
i) Bifilar strip construction.
ii) Coaxial tubular construction
iii) Squirrel Cage Construction.

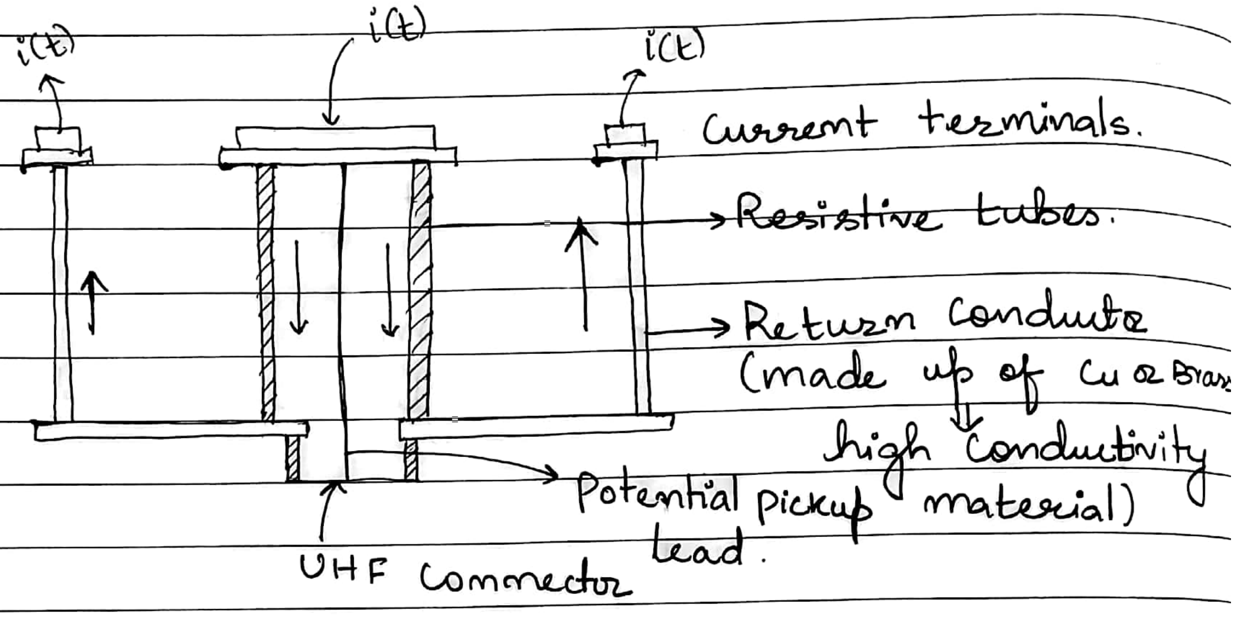
i) Bifilar Strip construction





→ Two wires are wound together, but currents in the two wires will flow in opposite direction & will thus Cancel magnetic field & thus inductance gets reduced.
→ UHF Connector is provided in order to put the Coaxial Cable terminals on opposite sides.
→ Insulating spacer is provided in order to keep the two ends apart from each other.

ii) Coaxial tubular Construction

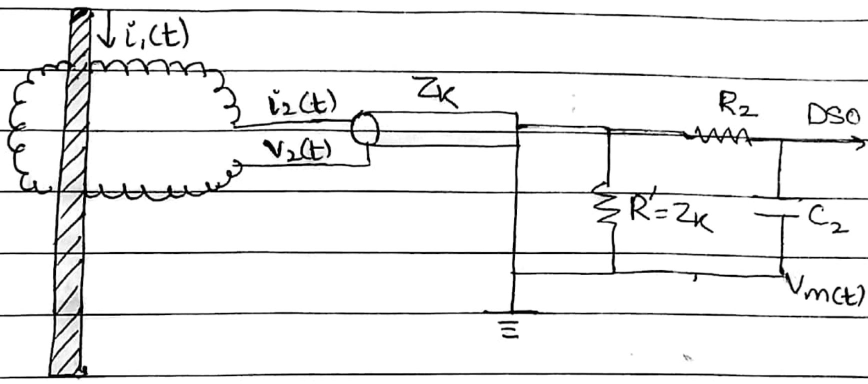


Since current in the two tubes flows in opposite direction and magnetic field gets cancelled. & thus inductance reduces.

iii) Squirrel Cage Construction

Similar Construction as that of co-axial tubular construction but here tubes are replaced by metallic bars.

2. Rogowski Coils



Toroidal coil having large no. of turns wound on a non-magnetic core (an air cored coil). It surrounds the conductor carrying huge impulse current to be measured.

$$V_2(t) = M\frac{di_1(t)}{dt} - i_2(t)R - L\frac{di_2(t)}{dt} \quad —①$$

$M\frac{di_1(t)}{dt}$: Induced voltage in coil due to mutual inductance.

$L\frac{di_2(t)}{dt}$: Induced voltage in coil due to self inductance.

$$i_2(t) << i_1(t)$$

Neglecting the 2nd two terms

$$V_2(t) = M\frac{di_1(t)}{dt} \quad —②$$

Output voltage is proportional to derivative of current. So, we require an integrating circuit. $V_m(t)$ will be the output voltage displayed on DSO

If passive integrating circuit is used

$$V_m(t) = \frac{1}{RC}\int_0^t V_2(t)\,dt$$

$$V_m(t) = \frac{M}{RC} i_1(t) \quad — (3)$$

$$\boxed{i_1(t) = \frac{RC}{M} V_m(t)}$$

This coil needs to be protected from electrostatic interaction so we put this coil in metallic non-magnetic shield (e.g Cu)

Dated:- 07-05-19

Magneto-optic Devices/Faraday Effect devices

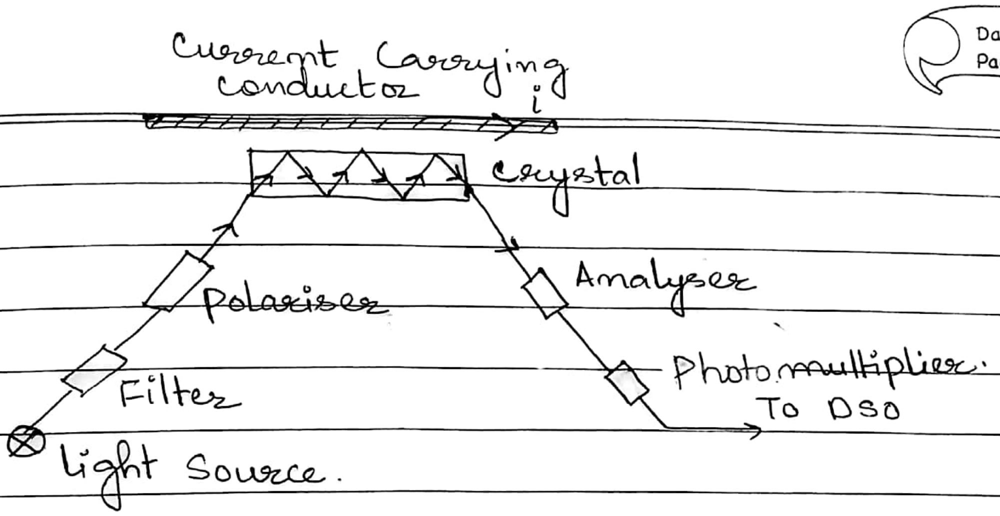
When a Linearly polarized-beam of light is passed through a transparent Crystal in presence of magnetic field, the plane of polarisation of light beam undergoes rotation. This is known as Faraday's effect. The angle of rotation α is given by

$$\alpha = VBL$$

Where V = Verdet constant which depends on wavelength of light.

B = magnetic flux density (in the direction of light)

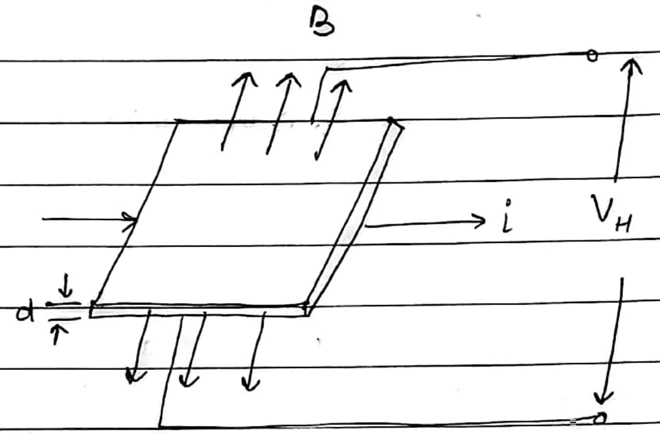
L = length of the path of light through the crystal taking into account the reflections within.



To measure the waveform of a large current, a beam of light from a stabilised light source is passed through a filter and polariser and is made incident on a crystal placed in the magnetic field produced by the current i as shown in the figure. The light beam undergoes rotation of its plane of polarisation. The output light is passed through an analyser & photomultiplier and the output of photomultiplier can be displayed on DSO.

The relationship between the displayed waveform and the current i is complex but can be determined. This method has an advantage that there is no direct electric connection between the source & the device & hence there are no insulation problems as well.

Hall Effect Transducers



If an electric current flows through a metallic plate located in a magnetic field perpendicular to its plane, lorentz forces will deflect electrons in the metallic plate in a direction normal to the direction of both the current & the magnetic field. The charge displacement produces an emf in the normal direction called the Hall Voltage. The Hall voltage is given by

$$V_H = R \frac{Bi}{d}$$

R = Hall Coefficient depends on the material used.

B = magnetic flux density.
i = current
d = thickness.

The Hall coefficient 'R' is high for semi-conductors & hence these are used for making the Hall elements.

In large current measurements, the current Carrying conductor is surrounded by a ferro-magnetic core and a Hall element is placed in a small air gap in the magnetic core. A small DC current is passed through the Hall element and the voltage developed across the Hall element is proportional to the magnetic field produced by the current to be measured.

Hall effect transducers Can be used for the measurement of DC, AC & impulse Currents.