High Voltage Engineering

UNIT-II

Measurement of High Voltages and Currents

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Measurement of High Voltages and Currents

Measurements of high voltages and currents involves much more complex problems which a specialist, in common electrical measurement, does not have to face. The high voltage equipments have large stray capacitances with respect to the grounded structures and hence large voltage gradients are set up.

A person handling these equipments and the measuring devices must be protected against these over voltages. For this, large structures are required to control the electrical fields and to avoid flash over between the equipment and the grounded structures. Sometimes, these structures are required to control heat dissipation within the circuits.

Therefore, the location and layout of the equipments is very important to avoid these problems. Electromagnetic fields create problems in the measurements

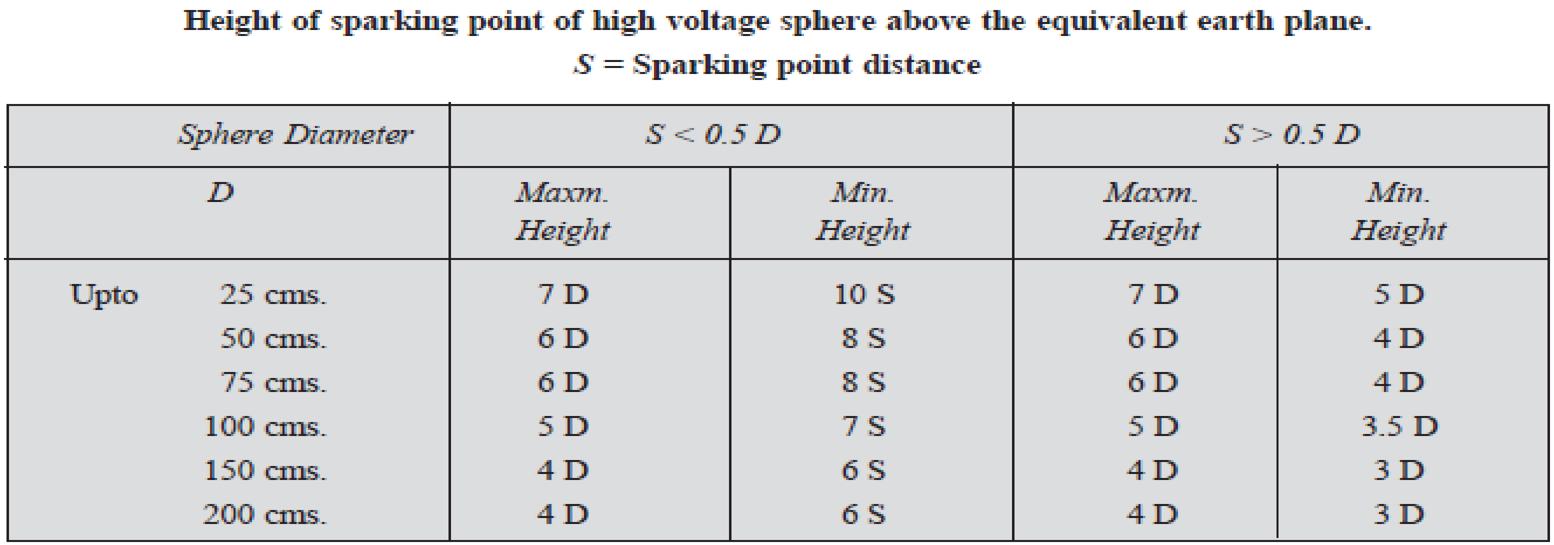
of impulse voltages and currents and should be minimised.

Sphere gap is by now considered as one of the standard methods for the measurement of peak value of d.c., a.c. and impulse voltages and is used for checking the voltmeters and other voltage measuring devices used in high voltage test circuits. Two identical metallic spheres separated by certain distance form a sphere gap.

The sphere gap can be used for measurement of impulse voltage of either polarity provided that the impulse is of a standard wave form and has wave front time at least 1 micro sec. and wave tail time of 5 micro sec. Also, the gap length between the sphere should not exceed a sphere radius.

If these conditions are satisfied and the specifications regarding the shape, mounting, clearances of the spheres are met, the results obtained by the use of sphere gaps are reliable to within ±3%. It has been suggested in standard specification that in places where the availability of ultraviolet radiation is low, irradiation of the gap by radioactive or other ionizing media should be used when voltages of magnitude less than 50 kV are being measured or where higher voltages with Accurate results are to be obtained.

According to BSS 358: 1939, when one sphere is grounded, the distance from the sparking point of the high voltage sphere to the equivalent earth plane to which the earthed sphere is connected should lie within the limits as given in Table



Height of sparking point of high voltage sphere above the equivalent earth plane.
S = Sparking point distance

Sphere Diameter	*$S < 0.5 D$*		*$S > 0.5 D$*	
D	*Maxm. Height*	*Min. Height*	*Maxm. Height*	*Min. Height*
Upto 25 cms.	7 D	10 S	7 D	5 D
50 cms.	6 D	8 S	6 D	4 D
75 cms.	6 D	8 S	6 D	4 D
100 cms.	5 D	7 S	5 D	3.5 D
150 cms.	4 D	6 S	4 D	3 D
200 cms.	4 D	6 S	4 D	3 D

In order to avoid corona discharge, the shanks supporting the spheres should be free from sharp edges and corners. The distance of the sparking point from any conducting surface except the shanks should be greater than

$$\left(25 + \frac{V}{3}\right) \text{cms}$$

where *V is the peak voltage is kV to be measured. When large spheres are used for the measurement of* low voltages the limiting distance should not be less than a sphere diameter.

Influence of Nearby Earthed Objects

The influence of nearby earthed object on the direct voltage breakdown of horizontal gaps was studied by Kuffel and Husbands. They surrounded the gap by a cylindrical metal cage and found that the breakdown voltage reduced materially especially when the gap length exceeded a sphere radius.

The experiments were conducted on 6.25 and 12.5 cm. diameter spheres when the radius of the surrounding metal cylinder (*B) was varied from 12.6 D to 4 D. The observation corresponding to 12.6 D was taken* as a reference. The reduction in the breakdown voltage for a given *S/D fitted closely into an empirical* relation of the form.

$$\Delta V = m \ln \frac{B}{D} + C$$

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Where Δ*V = per cent reduction in voltage in the breakdown voltage from the value when the* clearance was 12.6 *D, and m and C are the factors dependent on the ratio S/D.*

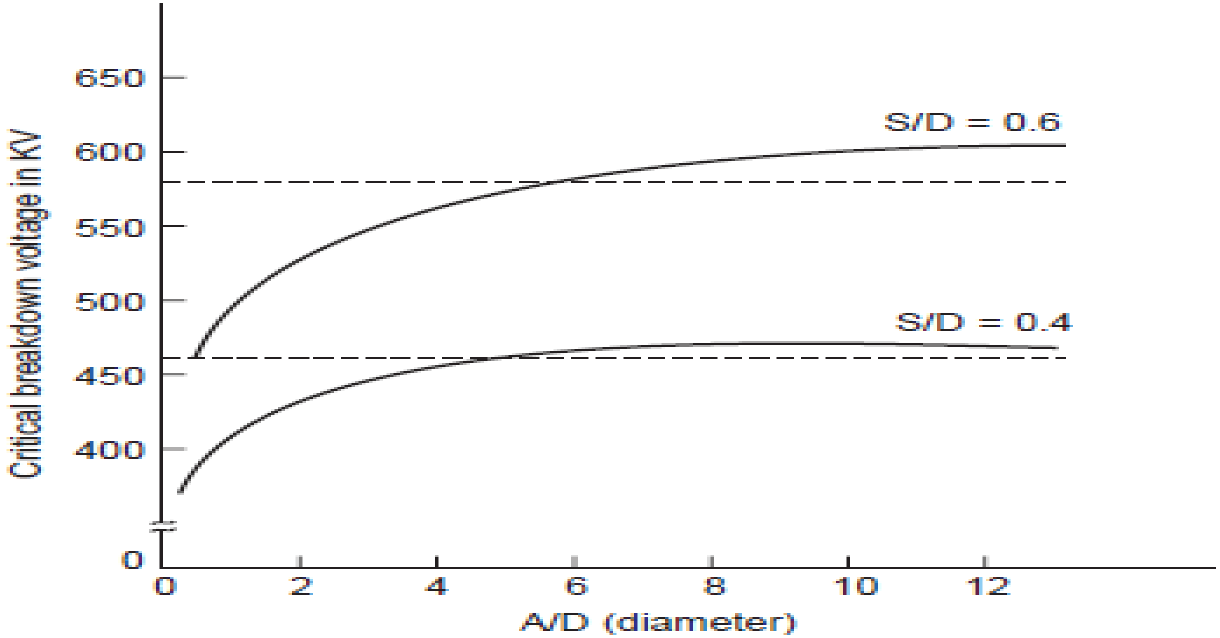


Fig. Breakdown voltage as a function of *A/D*

Influence of Humidity

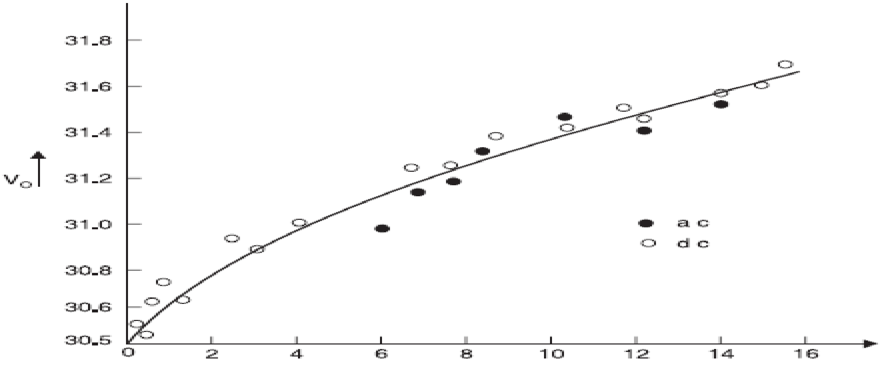


Fig. Breakdown voltage humidity relation for a.c. and d.c. for 1.0 cm gap between 25 cms diameter spheres

Fig. shows the effect of humidity on the breakdown voltage of a 25 cm diameter sphere with spacing of 1 cm when a.c. and d.c voltages are applied. It can be seen that

(*i) The a.c. breakdown voltage is slightly less than d.c. voltage.*

(*ii) The breakdown voltage increases with the partial pressure of water vapour.*

It has also been observed that

(*i) The humidity effect increases with the size of spheres and is largest for uniform field electrodes.*

(*ii) The voltage change for a given humidity change increase with gap length.*

The increase in breakdown voltage with increase in partial pressure of water vapour and this increase in voltage with increase in gap length is due to the relative values of ionisation and attachment coefficients in air.

Influence of Dust Particles

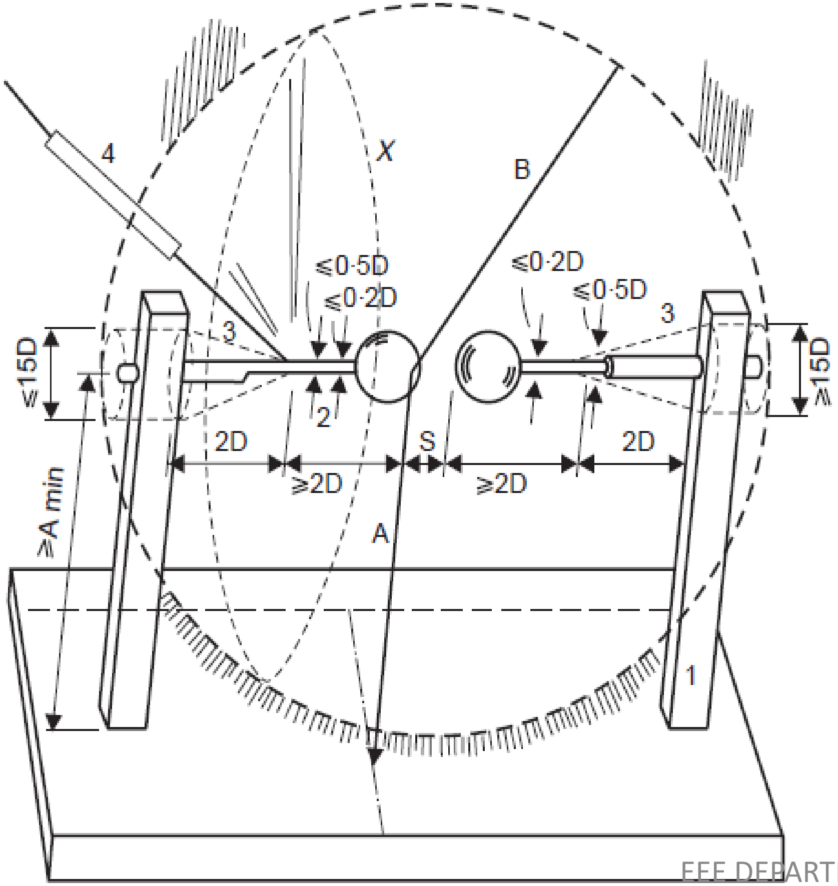
When a dust particle is floating between the gap this results into erratic breakdown in homogeneous or slightly inhomogenous electrode configurations.

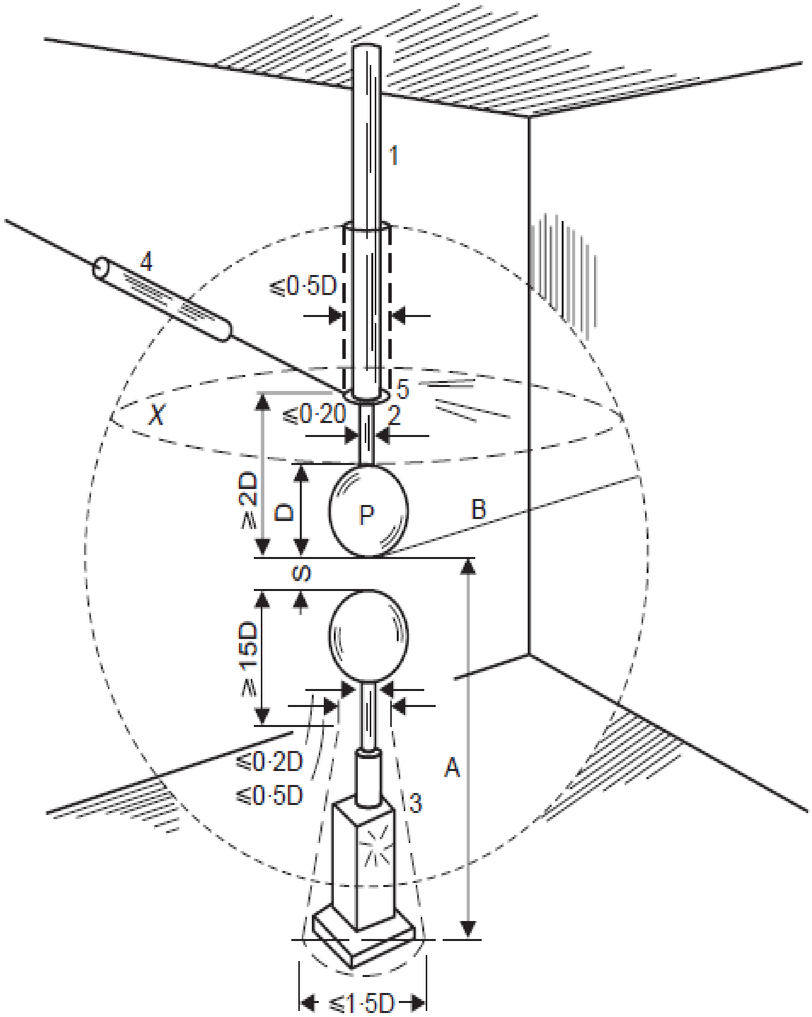
When the dust particle comes in contact with one electrode under the application of d.c. voltage, it gets charged to the polarity of the electrode and gets attracted by the opposite electrode due to the field forces and the breakdown is triggered shortly before arrival.

Gaps subjected to a.c. voltages are also sensitive to dust particles but the probability of erratic breakdown is less. Under d.c. voltages erratic breakdowns occur within a few minutes even for voltages as low as 80% of the nominal breakdown voltages. This is a major problem, with high d.c. voltage measurements with sphere gaps.

SPHERE GAP

Specifications on Spheres and Associated Accessories





UNIFORM FIELD SPARK GAPS

❑ Bruce suggested the use of uniform field spark gaps for the measurements of a.c., d.c. and impulse voltages.

❑These gaps provide accuracy to within 0.2% for a.c. voltage measurements an appreciable improvement as compared with the equivalent sphere gap arrangement.

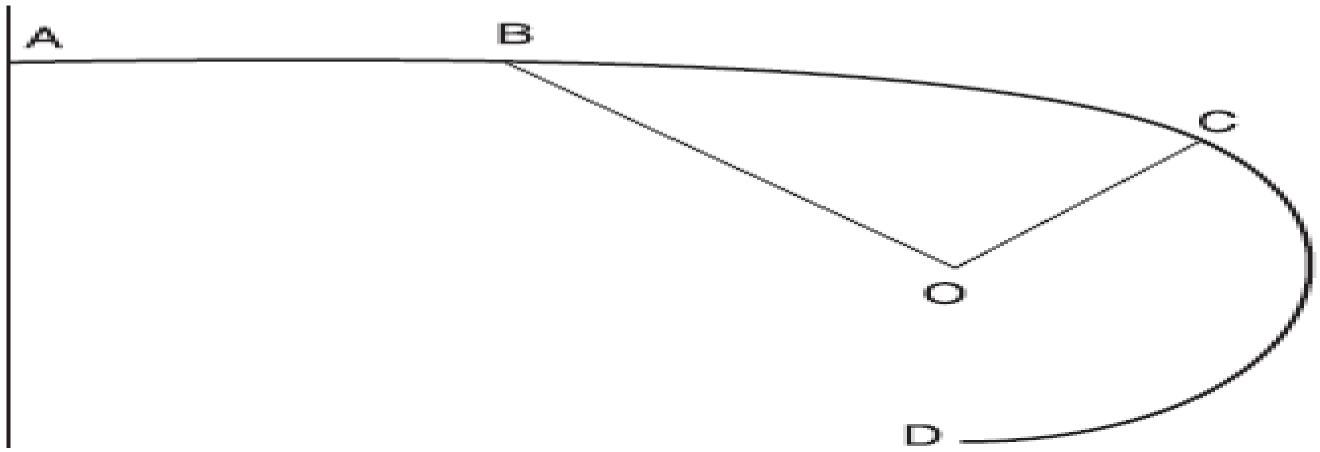


Fig. Half contour of uniform spark gap

❑A half-contour of one electrode having plane sparking surfaces with edges of gradually increasing curvature.

- The portion *AB is flat, the total diameter of the flat portion being greater than the maximum* spacing between the electrodes. The portion *BC consists of a sine curve based on the axes OB and OC* and given by $XY = CO \sin(BX/BO \cdot \pi/2)$. *CD is an arc of a circle with centre at O.*

- Bruce showed that the breakdown voltage *V of a gap of length S cms in air at 20°C and 760 mm* Hg. pressure is within 0.2 per cent of the value given by the empirical relation.

$$V = 24.22S + 6.08\sqrt{S}$$

The other advantages of uniform field spark gaps are
(i) No influence of nearby earthed objects
(ii) No polarity effect.

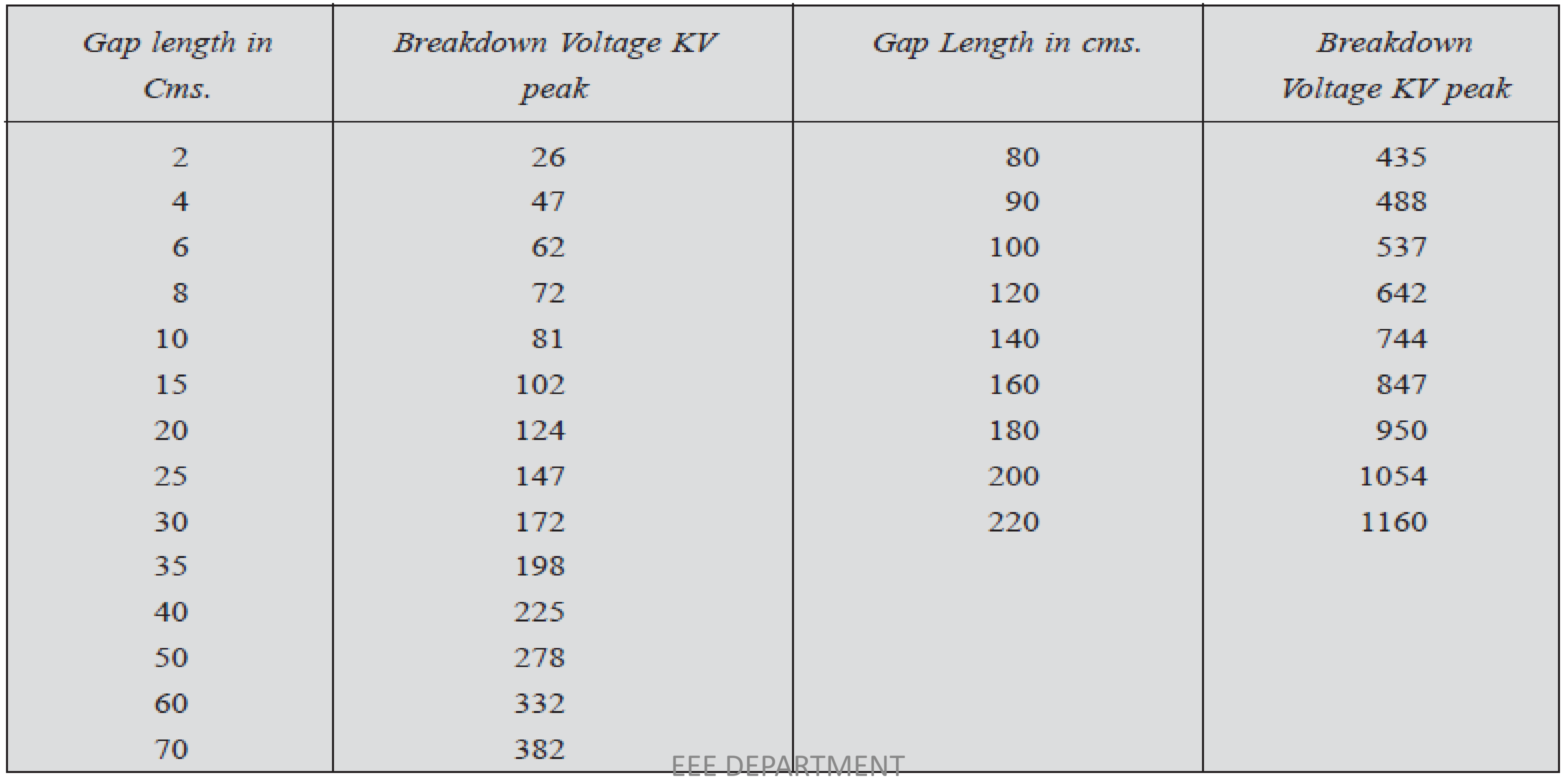
However, the disadvantages are
(i) Very accurate mechanical finish of the electrode is required.
(ii) Careful parallel alignment of the two electrodes.
(iii) Influence of dust brings in erratic breakdown of the gap. This is much more serious in these

- gaps as compared with sphere gaps as the highly stressed electrode areas become much larger.

ROD GAPS

- A rod gap may be used to measure the peak value of power frequency and impulse voltages

- The gap usually consists of two 1.27 cm square rod electrodes square in section at their end and are mounted on insulating stands so that a length of rod equal to or greater than one half of the gap spacing overhangs the inner edge of the support.



Gap length in Cms.	*Breakdown Voltage KV peak*	*Gap Length in cms.*	*Breakdown Voltage KV peak*
2	26	80	435
4	47	90	488
6	62	100	537
8	72	120	642
10	81	140	744
15	102	160	847
20	124	180	950
25	147	200	1054
30	172	220	1160
35	198		
40	225		
50	278		
60	332		
70	382		

❖ The breakdown voltage is a rod gap increases more or less linearly with increasing relative air density over the normal variations in atmospheric pressure. Also, the breakdown voltage increases with increasing relative humidity, the standard humidity being taken as 15.5 mm Hg.

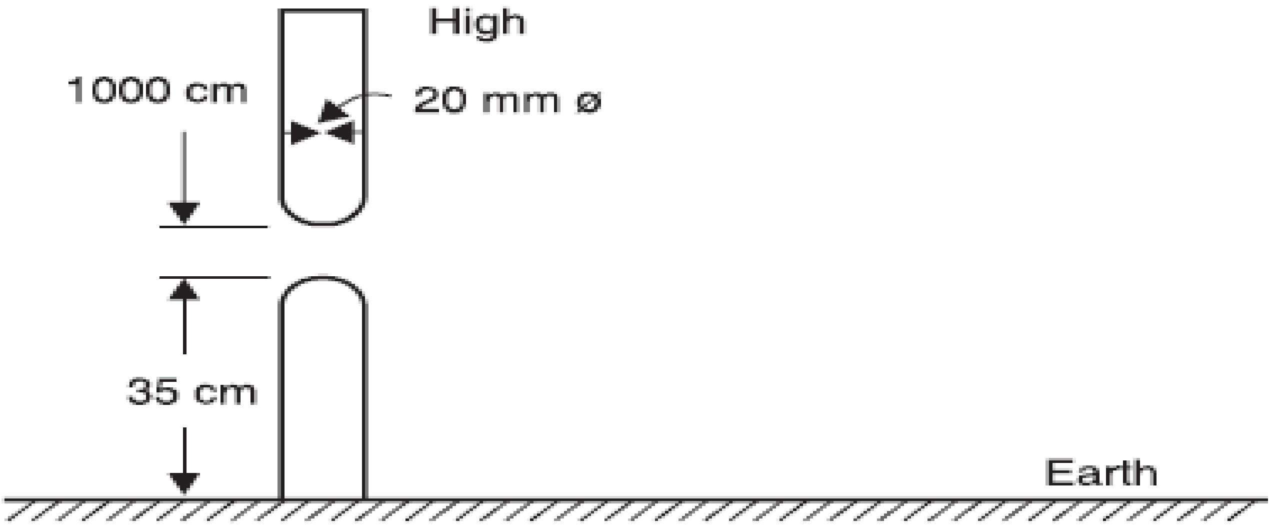


Fig. Electrode arrangement for a rod gap to measure HVDC

❖ The earthed electrode must be long enough to initiate positive breakdown streamers if the high voltage rod is the cathode.

- The breakdown voltage can be given by the empirical relation.

$$\boxed{V = \delta\,(A + BS)\;4\,\sqrt{5.1 \times 10^{-2}\,(h + 8.65)}\ \text{kV}}$$

where *h is the absolute humidity in gm/m3 and varies between 4 and 20 gm/m3 in the above relation.*

A = 20 kV for positive polarity

= 15 kV for negative polarity of the high voltage electrode.

The accuracy of the above relation is better than ±20% and, therefore, provides better accuracy even as compared to a sphere gap.

ELECTROSTATIC VOLTMETER

- The electric field according to Coulomb is the field of forces. The electric field is produced by voltage and, therefore, if the field force could be measured, the voltage can also be measured.

- Whenever a voltage is applied to a parallel plate electrode arrangement, an electric field is set up between the plates

- The field is uniform, normal to the two plates and directed towards the negative plate. If *A is the area of* the plate and *E is the electric field intensity between the plates ε the permittivity of the medium between* the plates, we know that the energy density of the electric field between the plates is given as,

$$W_d = \frac{1}{2} \varepsilon E^2$$

- Consider a differential volume between the plates and parallel to the plates with area *A and* thickness *dx, the energy content in this differential volume Adx is*

$$dW = W_d A dx = \frac{1}{2} \varepsilon E^2 A dx$$

➢Now force *F between the plates is defined as the derivative of stored electric energy along the* field direction *i.e.*,

$$\boxed{F = \frac{dW}{dx} = \frac{1}{2}\varepsilon E^2 A}$$

Now *E* = *V/d where V is the voltage to be measured and d the distance of separation between the* plates. Therefore, the expression for force

$$\boxed{F = \frac{1}{2}\varepsilon \frac{V^2 A}{d^2}}$$

➢ Since the two plates are oppositely charged, there is always force of attraction between the plates. If the voltage is time dependant, the force developed is also time dependant. In such a case the mean value of force is used to measure the voltage. Thus

$$\boxed{F = \frac{1}{T}\int_0^T F(t)dt = \frac{1}{T}\int \frac{1}{2}\varepsilon \frac{V^2(t)}{d^2} A\, dt = \frac{1}{2}\frac{\varepsilon A}{d^2} \cdot \frac{1}{T}\int V^2(t)dt = \frac{1}{2}\varepsilon A \frac{V_{rms}^2}{d^2}}$$

➢ Electrostatic voltmeters measure the force based on the above equations and are arranged such that one of the plates is rigidly fixed whereas the other is allowed to move. With this the electric field gets disturbed.

- For this reason, the movable electrode is allowed to move by not more than a fraction of a millimetre to a few millimetres even for high voltages so that the change in electric field is negligibly small. As the force is proportional to square of *Vrms, the meter can be used both for a.c. and d.c. voltage* measurement.
- For low range voltmeters, the upper frequency is generally limited to a few MHz.

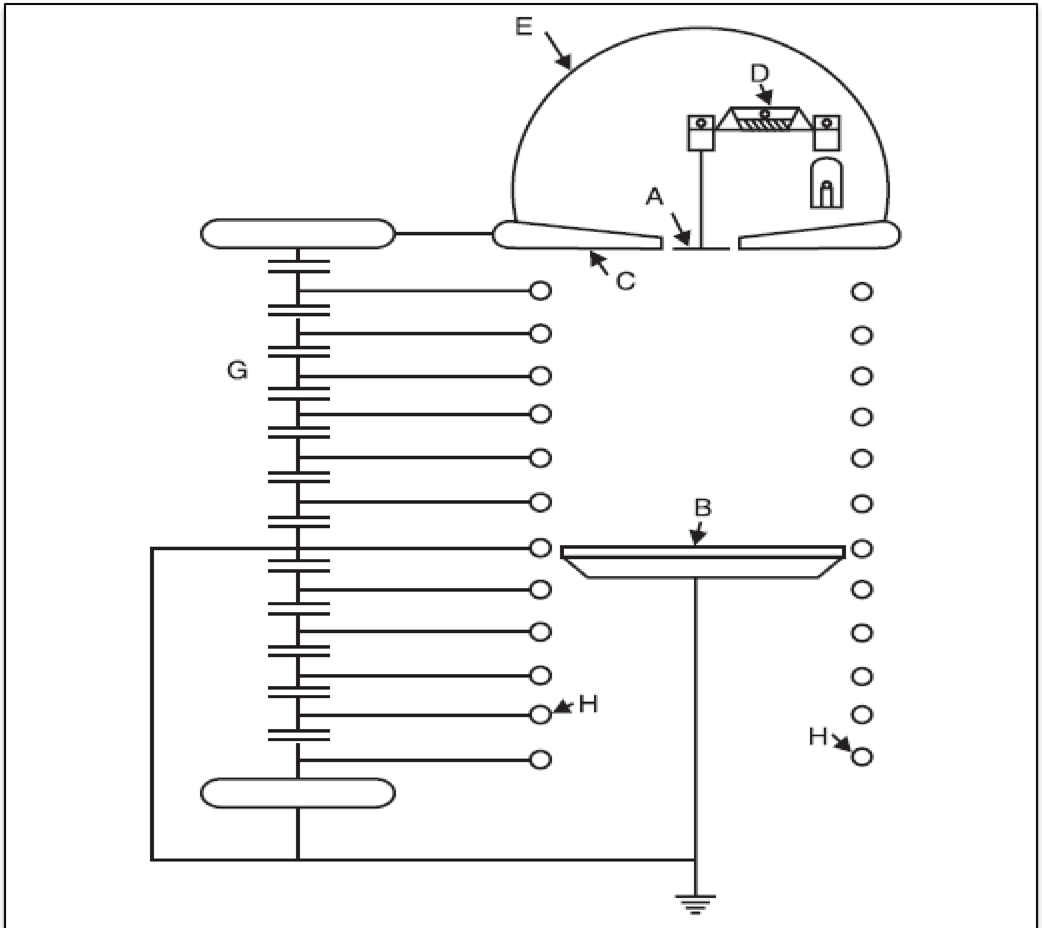


Fig. Schematic diagram of electrostatic voltmeter

D-Metal dome
B-Guard plate
P-Fixed plate
A-Movable plate
G-Guard loop or ring
D-Balance
C-Capacitance Driver

- The hemispherical metal dome *D encloses a sensitive balance B which measures the force of attraction between the movable* disc which hangs from one of its arms and the lower plate *P.*

- The movable electrode *M hangs with a* clearance of above 0.01 cm, in a central opening in the upper plate which serves as a guard ring. The diameter of each of the plates is 1 metre.

- Light reflected from a mirror carried by the balance beam serves to magnify its motion and to indicate to the operator at a safe distance when a condition of equilibrium is reached.

- As the spacing between the two electrodes is large (about 100 cms for a voltage of about 300 kV), the uniformity of the electric field is maintained by the guard rings *G which surround* the space between the discs *M and P.*

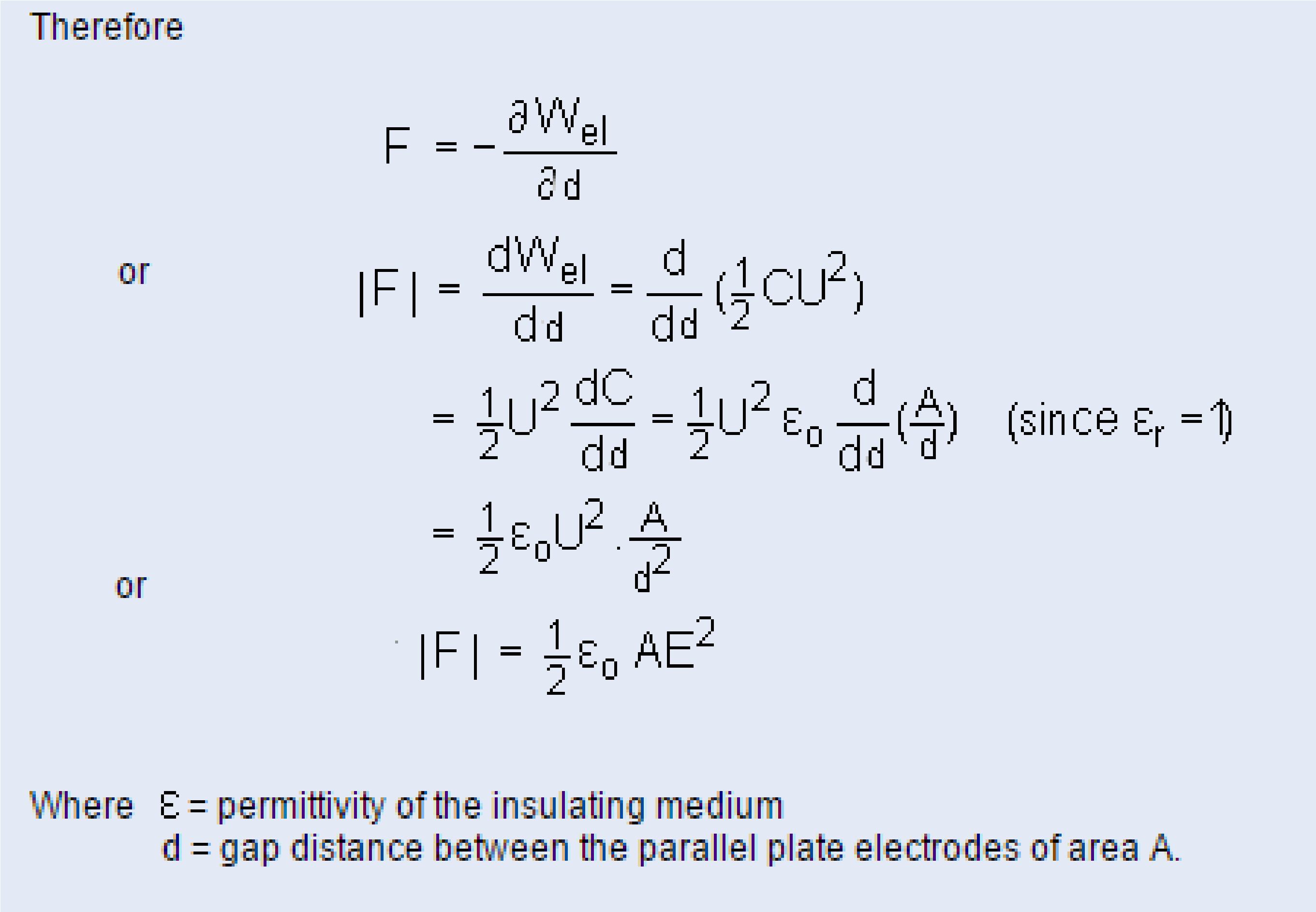
- The guard rings *G are maintained at a constant potential in space* by a capacitance divider ensuring a uniform spatial potential distribution. When voltages in the range 10 to 100 kV are measured, the accuracy is of the order of 0.01 per cent.

- Electrostatic voltmeters using compressed gas as the insulating medium have been developed.

- One such voltmeter using SF6 gas has been used which can measure voltages upto 1000 kV and accuracy is of the order of 0.1%.

Electrostatic Voltmeters

- Electrostatic Voltmeters produced upto 1000 kV rated voltage are suitable for the measurement of ac power frequency and also for higher frequency rms voltages. They can also measure dc voltages.
- For higher voltage range compact voltmeters with SF_6 gas or vaccum insulation gap are also produced.
- These voltmeters were suggested by Kelvin in 1884 for the measurement of rms value of power frequency voltage. They are developed to follow the Coulomb's law which defines the static electric field as a field of force.
- The field produced between two parallel plate electrodes with shaped profile brims, is a uniform field.
- If the voltage applied across these parallel plates having a gap distance 'd' is U, then the uniform field produced in the gap between them will have an intensity E equal to U/d.
- The attracting force F between the plates on area A of the electrodes is equal to the rate of change of stored electrical energy W_{el} per unit distance in the capacitance formed between the plates.



Therefore

$$F = -\frac{\partial W_{el}}{\partial d}$$

or

$$|F| = \frac{dW_{el}}{dd} = \frac{d}{dd}\left(\frac{1}{2}CU^2\right)$$

$$= \frac{1}{2}U^2\frac{dC}{dd} = \frac{1}{2}U^2\,\varepsilon_0\frac{d}{dd}\left(\frac{A}{d}\right) \quad (\text{since } \varepsilon_r = 1)$$

$$= \frac{1}{2}\varepsilon_0 U^2 \cdot \frac{A}{d^2}$$

or

$$|F| = \frac{1}{2}\varepsilon_0\, AE^2$$

Where ε = permittivity of the insulating medium

d = gap distance between the parallel plate electrodes of area A.

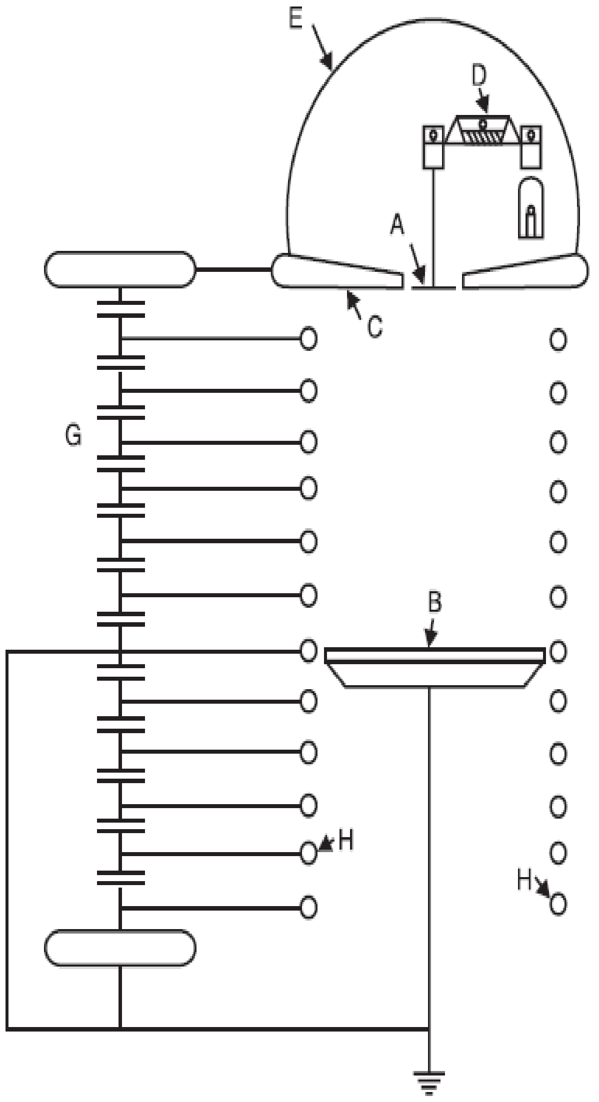


Fig. Schematic diagram of electrostatic voltmeter

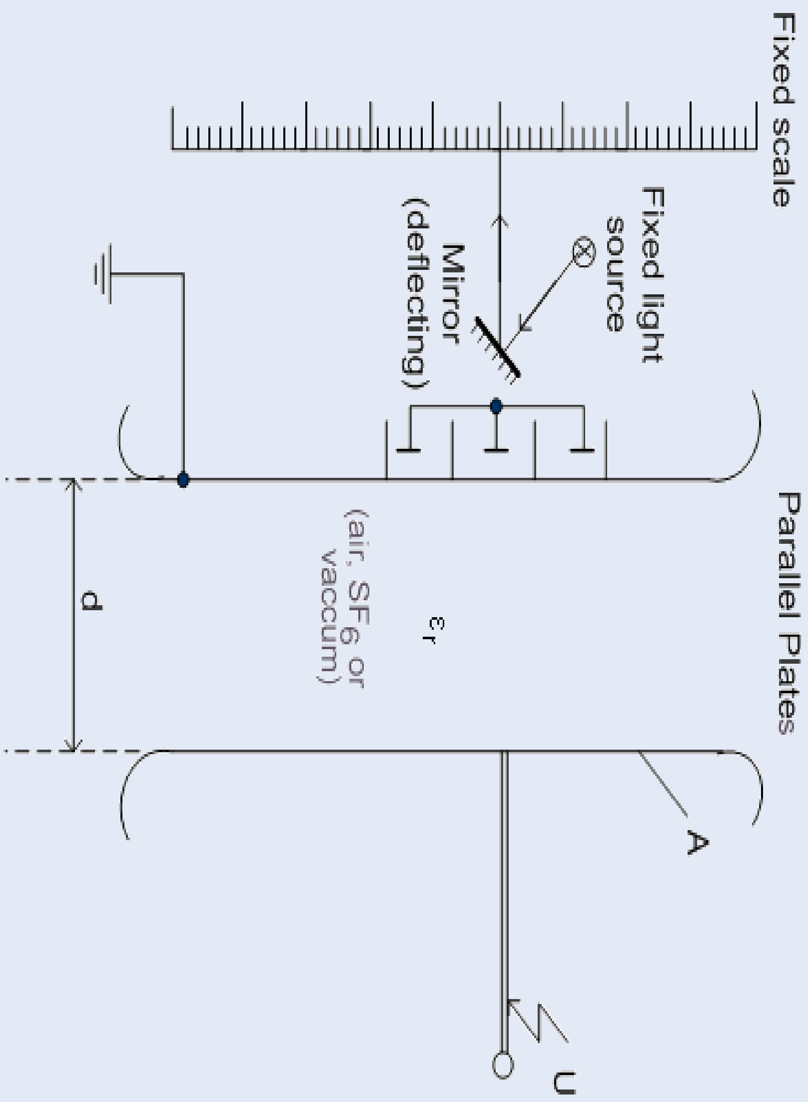


Fig — Schematic of an Electrostatic Voltmeter

The attracting force is always positive independent of the polarity of the voltage. If the voltage is not constant, the force is also time (frequency) dependent. Then the mean value of the force is used to measure the rms value of the voltage. Thus

$$\frac{1}{T}\int_0^T F(t)\,dt = \frac{\varepsilon_0 A}{2d^2}\cdot\frac{1}{T}\int_0^T u^2(t)\,dt = \frac{\varepsilon_0 A}{2d^2}(U_{rms})^2$$

where T is a proper integration time.

- Electrostatic voltmeters are arranged such that one of the electrodes or a part of it is allowed to move.
- Thus electrostatic voltmeters are rms indicating instruments if the force integration and its display follows eqn-32.2.
- Various voltmeters developed differ in their use of different methods of restoring forces required to balance the electrostatic attraction. This can be achieved by suspension of the moving electrode on one arm of a balance or its suspension on a spring or the use of a pendulous or torsional suspension.
- The small movement is generally transmitted and amplified by a spot light and mirror system, but many other systems have also been used.
- The electrostatic measuring device can be used for absolute voltage measurements since the calibration can be made in terms of the fundamental quantities of the gap length and forces.
- For a constant electrode separation 'd' the integrated forces increase with $(U_{rms})^2$ and thus the sensitivity of the system for low ranges of the rated voltages of the instrument is small. This disadvantage is overcome, however by varying the gap length in appropriate steps.
- The high pressure gas or even high vacuum between the electrodes provide very high resistivity, therefore the low active power loss.
- The measurement of voltages lower than about 50V is , however not possible as the forces become too small.
- The load inductance and the electrode system capacitance, however, form a series resonant circuit which must be damped, thus limiting the frequency range.

GENERATING VOLTMETER

- 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 measuring Source

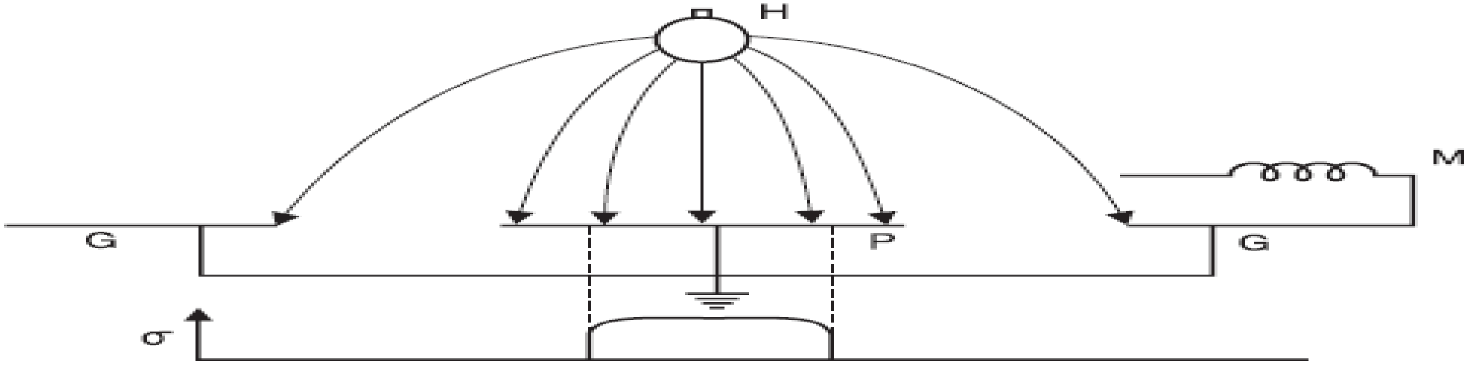


Fig. Principle of generating voltmeter

- *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.*

- 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.*

$$i\,(t) = \frac{dq(t)}{dt} = \frac{d}{dt}\left[\int \sigma\,(a)da\right]$$

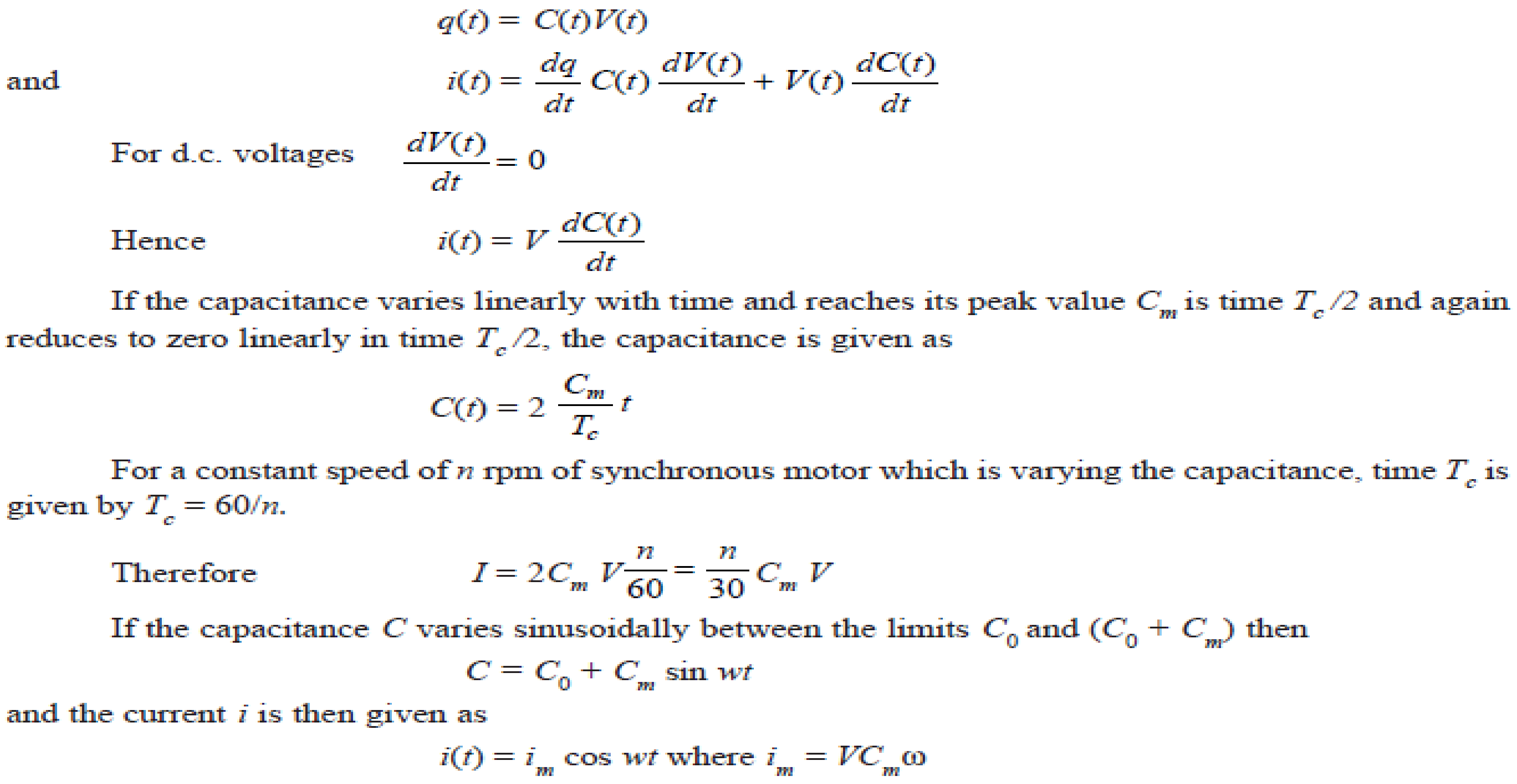
- Where σ (*a) is the electric field density or charge density along some path and is assumed constant over* the differential area *da of the pick up electrode.*

- The area of the pick up electrode exposed to the electric field is changing, the current *i(t) is given bv*

$$i(t) = \frac{d}{dt}\int_{A(t)} \sigma(a)da = \varepsilon\frac{d}{dt}\int_{A(t)} E(a)da$$

- where σ (*a) = εE(a) and ε is the permittivity of the medium between the high voltage electrode and the* grounded electrode.

- ❖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*



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

and $$i(t) = \frac{dq}{dt}\, C(t)\,\frac{dV(t)}{dt} + V(t)\,\frac{dC(t)}{dt}$$

For d.c. voltages $$\frac{dV(t)}{dt} = 0$$

Hence $$i(t) = V\,\frac{dC(t)}{dt}$$

If the capacitance varies linearly with time and reaches its peak value C_m is time $T_c/2$ and again reduces to zero linearly in time $T_c/2$, the capacitance is given as

$$C(t) = 2\,\frac{C_m}{T_c}\,t$$

For a constant speed of n rpm of synchronous motor which is varying the capacitance, time T_c is given by $T_c = 60/n$.

Therefore $$I = 2C_m\,V\frac{n}{60} = \frac{n}{30}\,C_m\,V$$

If the capacitance C varies sinusoidally between the limits C_0 and $(C_0 + C_m)$ then

$$C = C_0 + C_m \sin wt$$

and the current i is then given as

$$i(t) = i_m \cos wt \text{ where } i_m = VC_m\omega$$

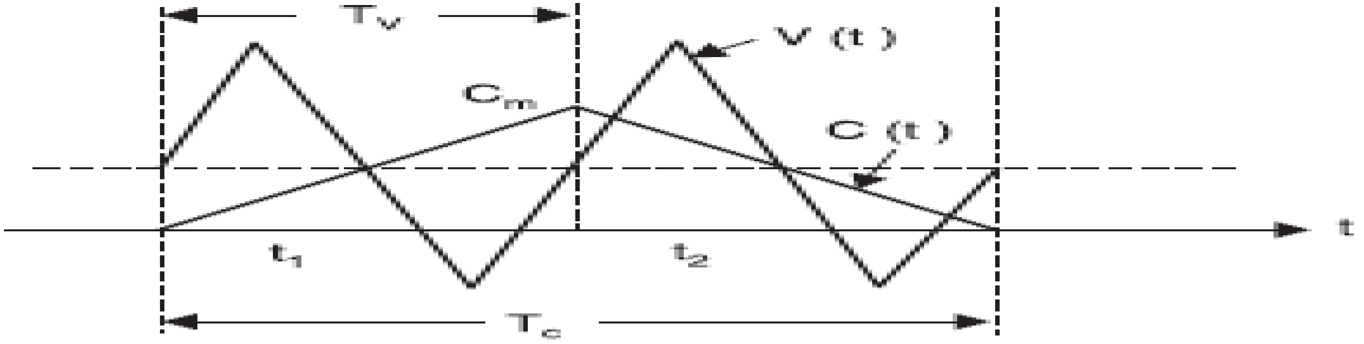


Fig. · Capacitance and voltage variation

the instantaneous value of current *$i(t) = C_m f_v V(t)$ where $f_v = 1/T_v$ the frequency of voltage.*Since *$f_v = 2f_c$ and $f_c = 60/n$ we obtain $I(t) = n/30\, C_m V(t)$*

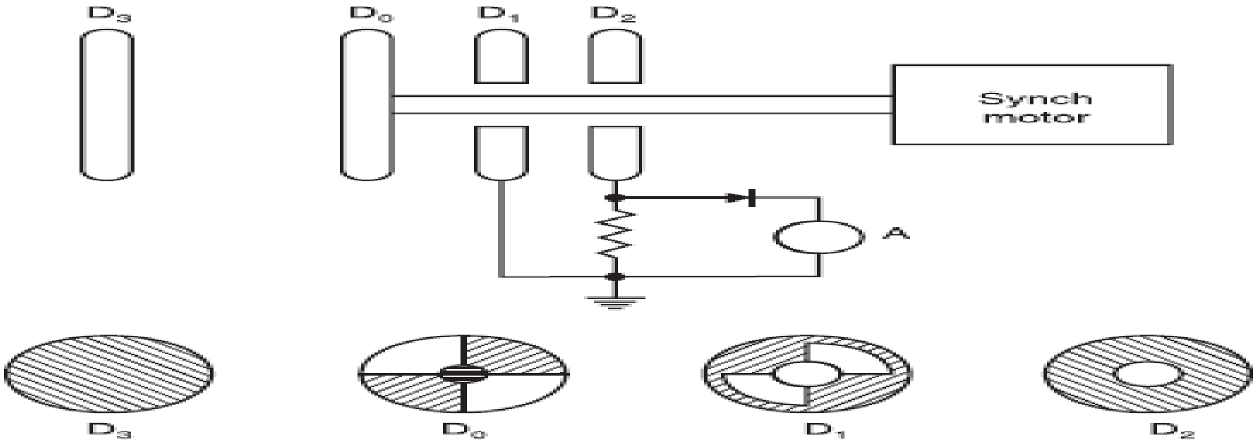


Fig. Schematic diagram of generating voltmeter

Generating voltmeters are linear scale instruments and applicable over a wide range of voltages.
The sensitivity can be increased by increasing the area of the pick up electrode and by using amplifier circuits.

The main advantages of generating voltmeters are
(*i) scale is linear and can be extrapolated*
(*ii) source loading is practically zero*
(iii) no direct connection to the high voltage electrode.

THE CHUBB-FORTESCUE METHOD

❖ Chubb and Fortescue suggested a simple and accurate method of measuring peak value of a.c. voltages.

❖ The basic circuit consists of a standard capacitor, two diodes and a current integrating ammeter (MC ammeter)

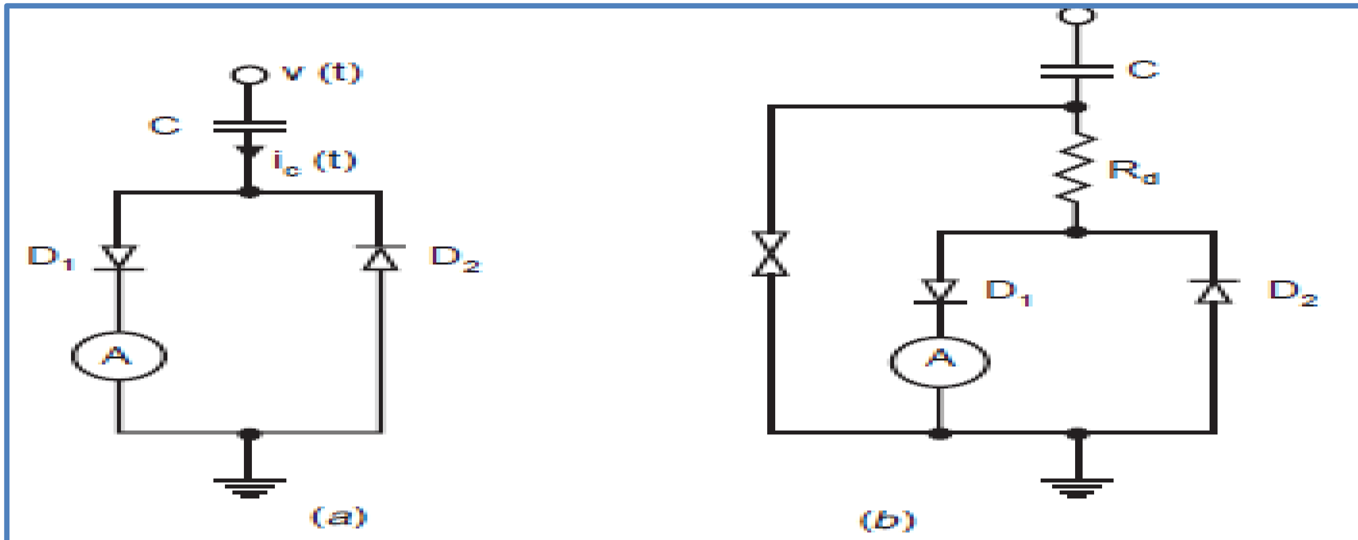
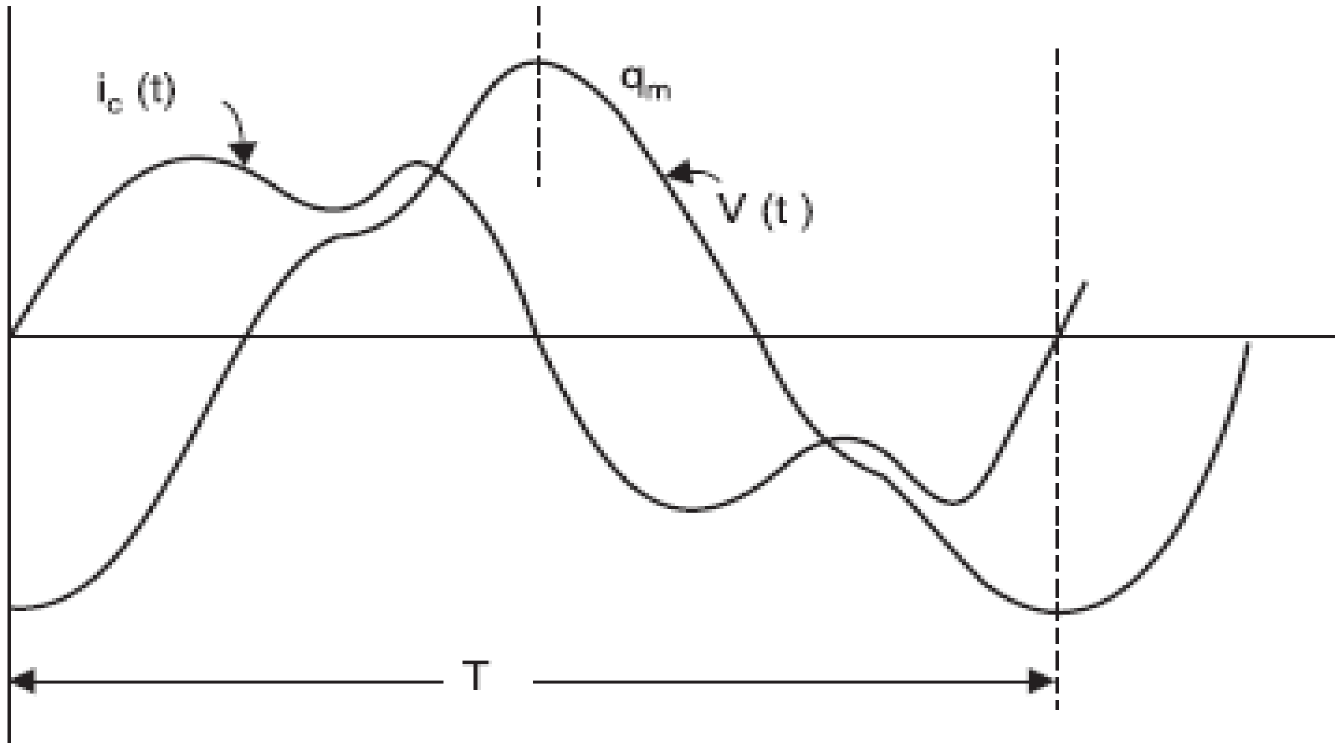


Fig. (a) Basic circuit (b) Modified circuit

The ammeter reads the mean value of the current.

$$I = \frac{1}{T}\int_{t_1}^{t_2} C\,\frac{dv(t)}{dt}\,.\,dt = \frac{C}{T}\,.\,2V_m = 2V_m fC \text{ or } V_m = \frac{I}{2fC}$$

The displacement current *ic(t), Fig. is given by the rate of change of the charge and hence* the voltage *V(t) to be measured flows through the high voltage capacitor C and is subdivided into* positive and negative components by the back to back connected diodes.



Digital Peak Voltage measuring circuit

❖The rectified current is not measured directly, instead a proportional analog voltage signal is derived which is then converted into a proportional medium frequency for using a voltage to frequency convertor

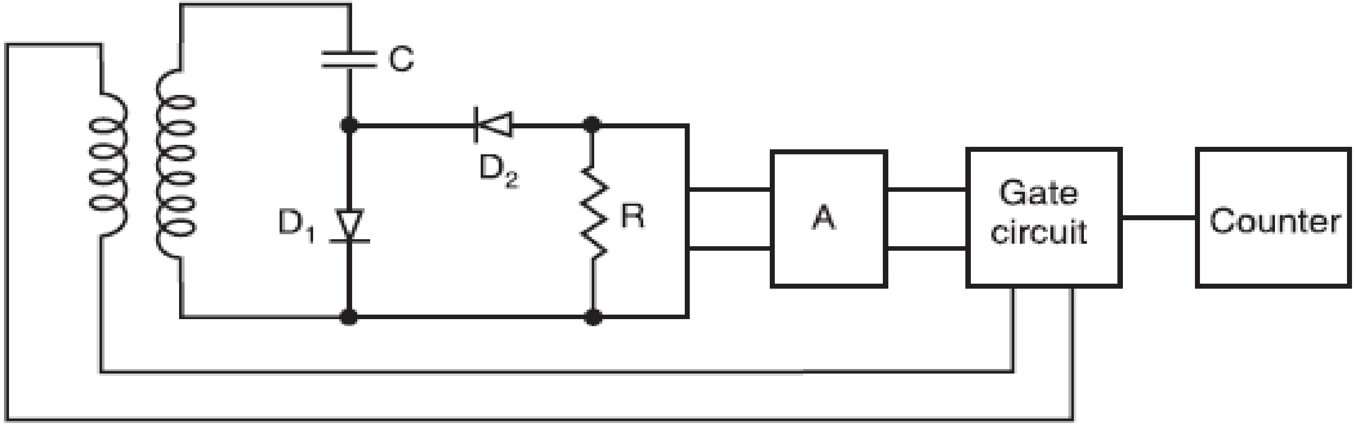
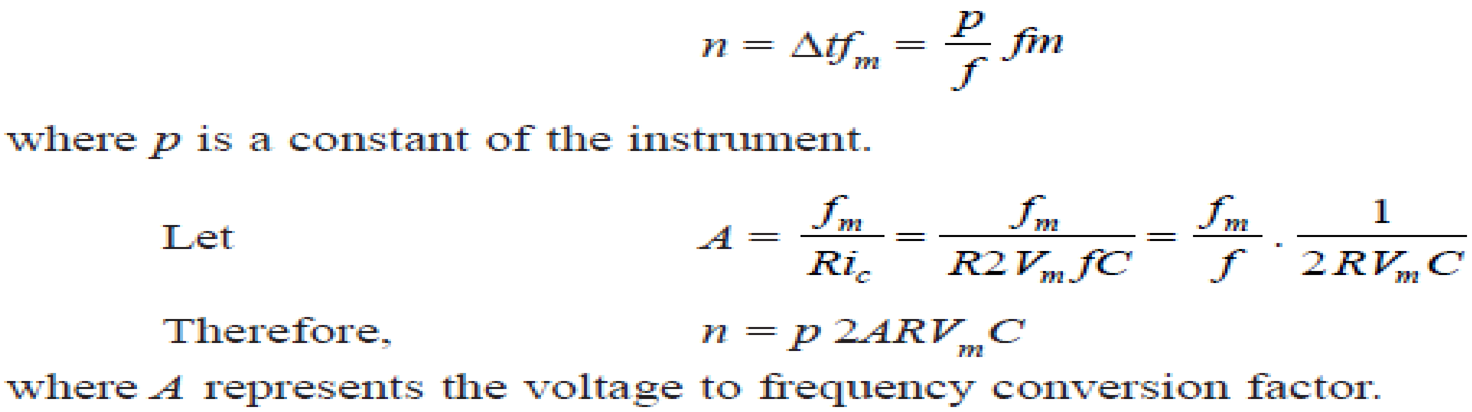


Fig. Digital peak voltmeter

The frequency ratio *fm/f is measured with a gate circuit controlled by the a.c.* power frequency (supply frequency *f) and a counter that opens for an adjustable number of period* $\Delta t = p/f$*. The number of cycles n counted during this interval is*



$$n = \Delta t f_m = \frac{p}{f} fm$$

where p is a constant of the instrument.

Let $$A = \frac{f_m}{R i_c} = \frac{f_m}{R 2 V_m f C} = \frac{f_m}{f} \cdot \frac{1}{2 R V_m C}$$

Therefore, $$n = p\, 2 A R V_m C$$

where A represents the voltage to frequency conversion factor.

Thus the indicator can be calibrated to read *Vm directly by selecting suitable values of A, p and R.*

The voltmeter is found to given an accuracy of 0.35%.

Peak Voltmeters with Potential Dividers

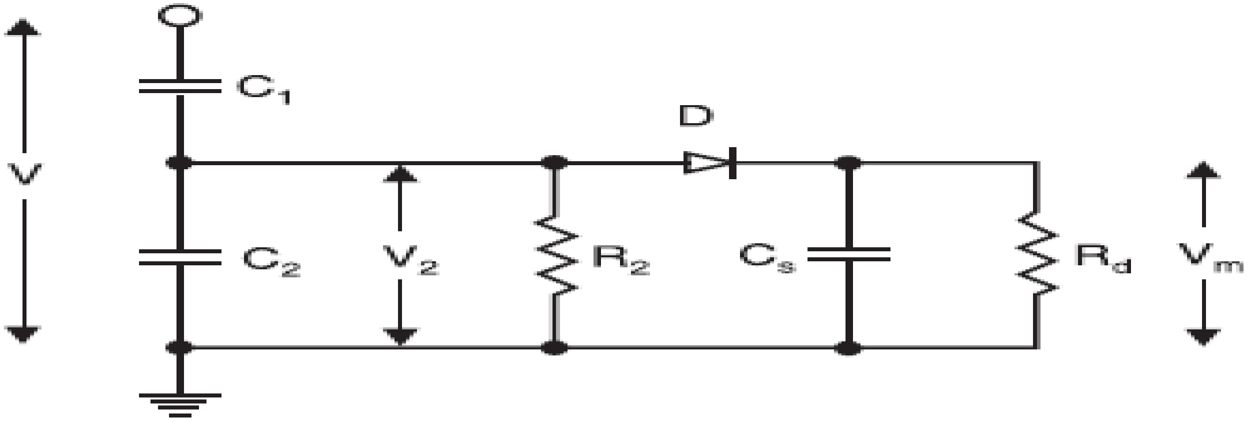


Fig. Peak voltmeter

- a simple peak voltmeter circuit consisting of a capacitor voltage divider which reduces the voltage *V to be measured to a* low voltage *Vm.*

- Suppose *R2 and Rd are not present and the supply voltage is V. The voltage across the storage* capacitor *Cs will be equal to the peak value of voltage across C2 assuming voltage drop across the diode* to be negligibly small. The voltage could be measured by an electrostatic voltmeter or other suitable voltmeters with very high input impedance.

  - Voltage across C2 is smaller than the voltage across Cs

    Choose RdCs≈1 sec

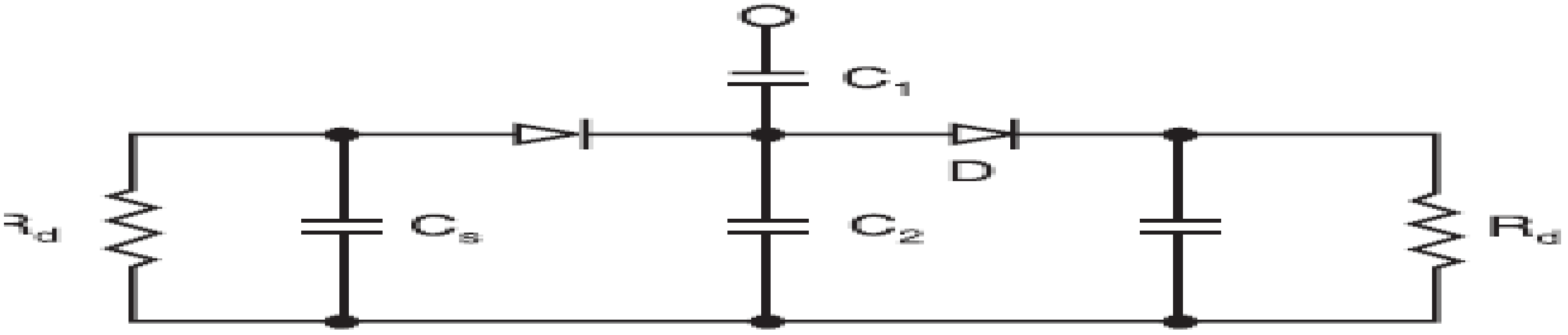


Fig. Modified peak voltmeter circuit

$$e_r = 2e_d \frac{C_s}{C_1 + C_2 + C_s}$$

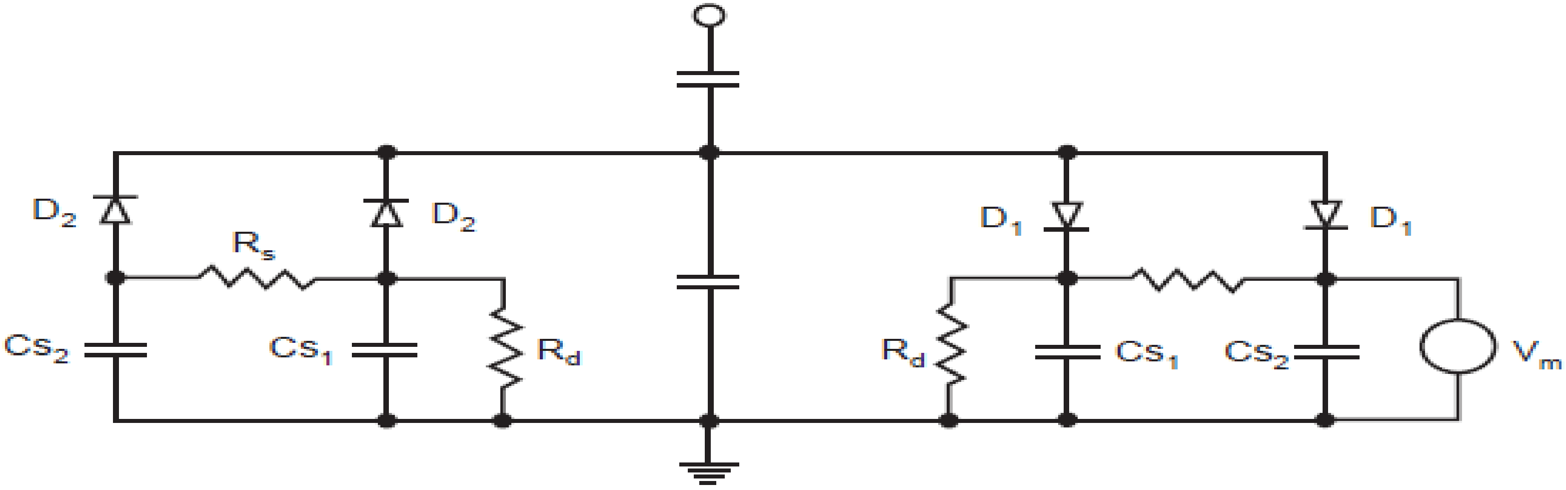


Fig. Two-way booster circuit designed by Rabus

IMPULSE VOLTAGE MEASUREMENTS USING VOLTAGE DIVIDERS

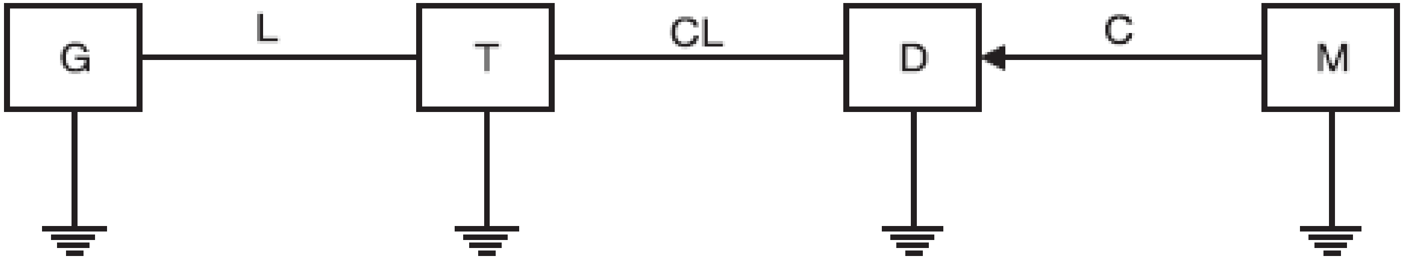


Fig. . Basic voltage testing circuit

A layout of a voltage testing circuit within a high voltage testing area. The voltage generator *G is* connected to a test object—*T through a lead L.*

These three elements form a voltage generating system. The lead *L consists of a lead wire and* a resistance to damp oscillation or to limit short-circuit currents if of the test object fails.

The measuring system starts at the terminals of the test object and consists of a connecting lead *CL to the voltage* divider *D. The output of the divider is fed to the measuring instrument (CRO etc.) M.*

Voltage Divider

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.

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.

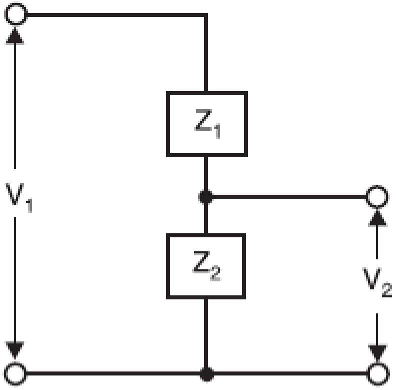


Fig. Basic diagram of a potential divider circuit

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 potential divider is most simply represented by two impedances *Z1 and Z2 connected in series and the sample voltage* required for measurement is taken from across *Z2.*

If the voltage to be measured is *V1 and sampled voltage V2,*then

$$V_2 = \frac{Z_2}{Z_1 + Z_2} V_1$$

If the impedances are pure resistances $V_2 = \frac{R_2}{R_1 + R_2} V_1$

and in case pure capacitances are used $V_2 = \frac{C_1}{C_1 + C_2} V_1$

The voltage *V2 is normally only a few hundred volts and hence the value of Z2 is so chosen that V2 across it gives sufficient deflection on a CRO.*

Resistance Potential Dividers

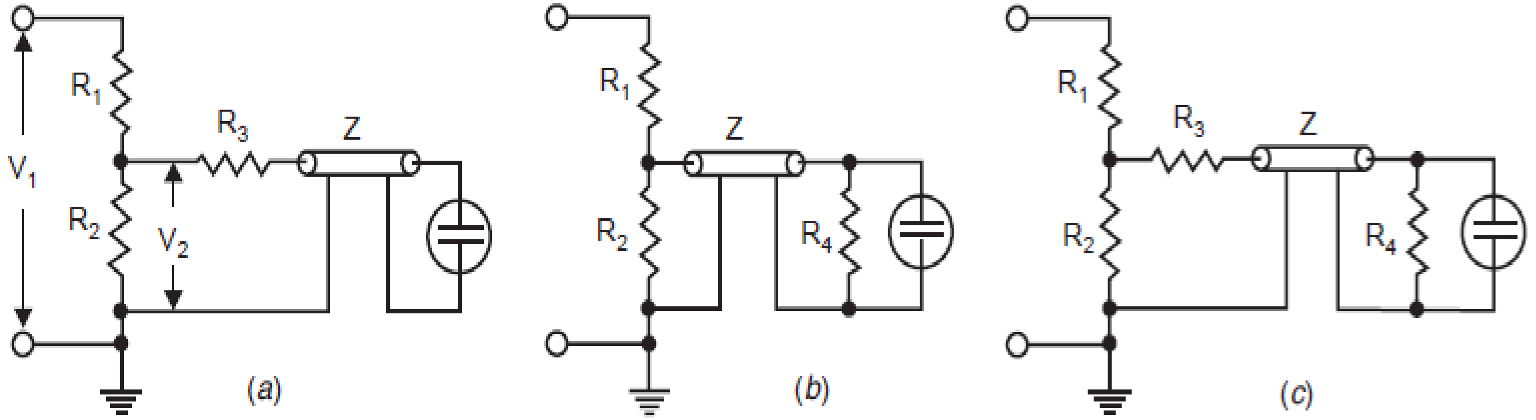


Fig. Various forms of resistance potential dividers recording circuits (*a*) Matching at divider end (*b*) Matching at Oscillograph end (*c*) Matching at both ends of delay cable

Here R_3, the resistance at the divider end of the delay cable is chosen such that $R_2 + R_3 = Z$ which puts an upper limit on R_2 *i.e.,* $R_2 < Z$. In fact, sometimes the condition for matching is given as

$$Z = R_3 + \frac{R_1 R_2}{R_1 + R_2}$$

But, since usually $R_1 >> R_2$, the above relation reduces to $Z = R_3 + R_2$. From Fig. 4.19 (*a*), the voltage appearing across R_2 is

$$V_2 = \frac{Z_1}{Z_1 + R_1} V_1$$

where Z_1 is the equivalent impedance of R_2 in parallel with $(Z + R_3)$, the surge impedance of the cable being represented by an impedance Z to ground.

Now $$Z_1 = \frac{(Z + R_3)R_2}{R_2 + Z + R_3} = \frac{(Z + R_3)R_2}{2Z}$$

Therefore, $$V_2 = \frac{(Z + R_3)R_2}{2Z} \frac{V_1}{Z_1 + R_1}$$

However, the voltage entering the delay cable is

$$V_3 = \frac{V_2}{Z + R_3} Z = \frac{Z}{Z + R_3} \frac{(Z + R_3)R_2}{2Z} \cdot \frac{V_1}{Z_1 + R_1} = V_1 \frac{R_2}{2(Z_1 + R_1)}$$

As this voltage wave reaches the CRO end of the delay cable, it suffers reflections as the impedance offered by the CRO is infinite and as a result the voltage wave transmitted into the CRO is doubled. The CRO, therefore, records a voltage

$$V_3' = \frac{R_2}{Z_1 + R_1} V_1$$

Equivalent impedance

$$= R_1 + \frac{R_2 Z}{R_2 + Z} = \frac{R_1(R_2 + Z) + R_2 Z}{(R_2 + Z)}$$

Therefore, Current $$I = \frac{V_1(R_2 + Z)}{R_1(R_2 + Z) + R_2 Z}$$

and voltage $$V_2 = \frac{I R_2 Z}{R_2 + Z} = \frac{V_1(R_2 + Z)}{R_1(R_2 + Z) + R_2 Z} \frac{R_2 Z}{R_2 + Z}$$

$$= \frac{R_2 Z}{R_1(R_2 + Z) + R_2 Z} V_1$$

or voltage ratio $$\frac{V_2}{V_1} = \frac{R_2 Z}{R_1(R_2 + Z) + R_2 Z}$$

Due to the matching at the CRO end of the delay cable, the voltage does not suffer any reflection at that end and the voltage recorded by the CRO is given as

$$V_2 = \frac{R_2 Z\, V_1}{R_1(R_2 + Z) + R_2 Z} = \frac{R_2 Z V_1}{(R_1 + R_2)Z + R_1 R_2} = \frac{R_2 V_1}{(R_1 + R_2) + \frac{R_1 R_2}{Z}}$$

Normally for undistorted wave shape through the cable

$$Z \approx R_2$$

Therefore,

$$V_2 = \frac{R_2}{2R_1 + R_2} V_1 \qquad V_2 = \frac{R_2}{2(R_1 + R_2)} V_1$$

Capacitance Potential Dividers

For measurement of impulse voltages not exceeding 1 MV capacitance dividers can be both portable and transportable

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 *C2 and the matching resistor if required.*

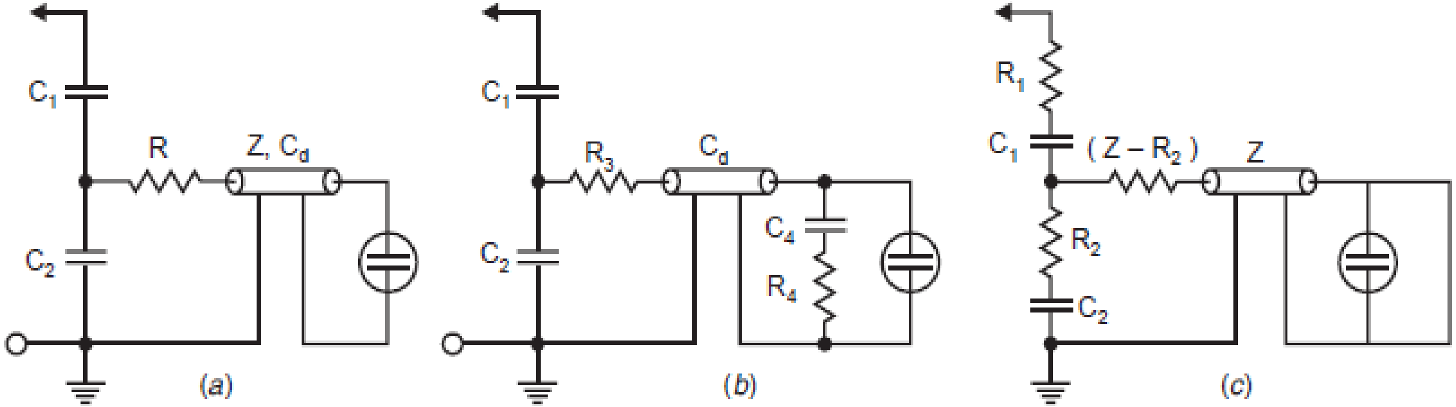


Fig. . Capacitor dividers (*a*) Simple matching (*b*) Compensated matching (*c*) Damped capacitor divider simple matching

The transformation ratio, therefore, changes from the value:

$$\frac{C_1 + C_2}{C_1}$$

for very high frequencies to the value

$$\frac{C_1 + C_2 + C_d}{C_1}$$

for low frequencies.

However, the capacitance of the delay cable *Cd is usually small as compared with C2.*

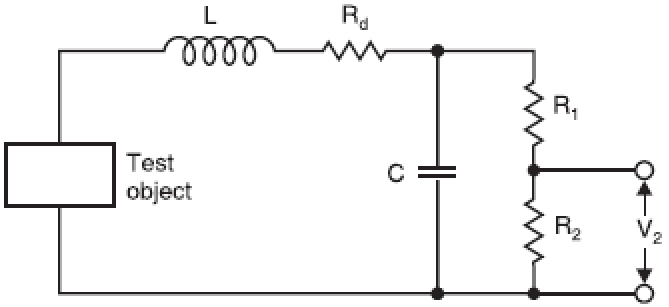


Fig. Simplified diagram of a resistance potential divider

a resistance potential divider after taking into considerations the lead in connection as the inductance and the stray capacitance as lumped capacitance.
Here *L represents the loop inductance of the lead-in connection for the high voltage arm.*

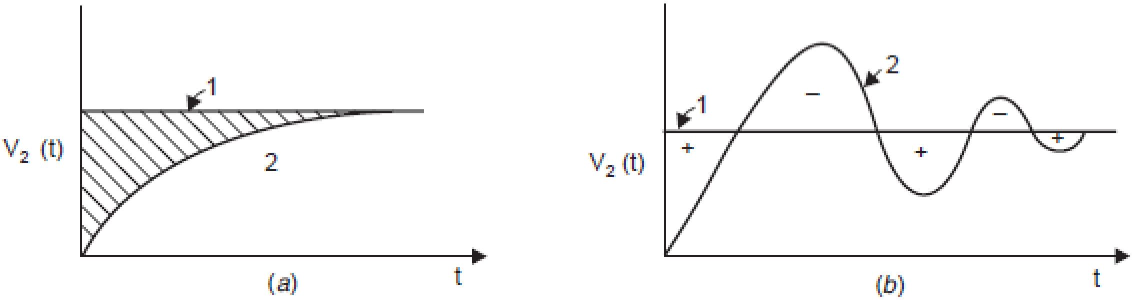


Fig. The response of resistance voltage divider

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.

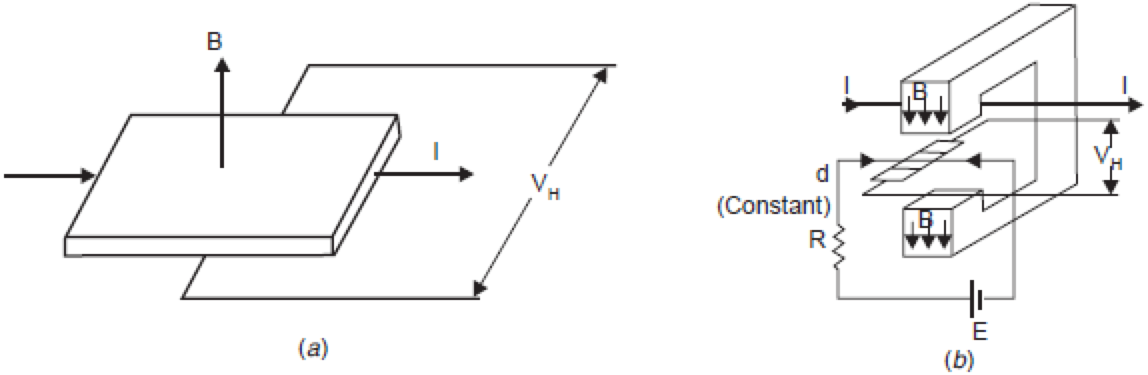
High Direct Currents

Low resistance shunts are used for measurement of these currents. The voltage drop across the shunt resistance is measured with the help of a millivoltmeter. 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.

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 electronsin 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.,*

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



(*a*)

(*b*)

Fig. Hall generator

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.

The magnetic field intensity produced by the conductor in the air gap at a depth *d is given by*

$$H = \frac{1}{2\pi d}$$

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. shows a scheme for current* measurements using current transformers and electro-optical technique.

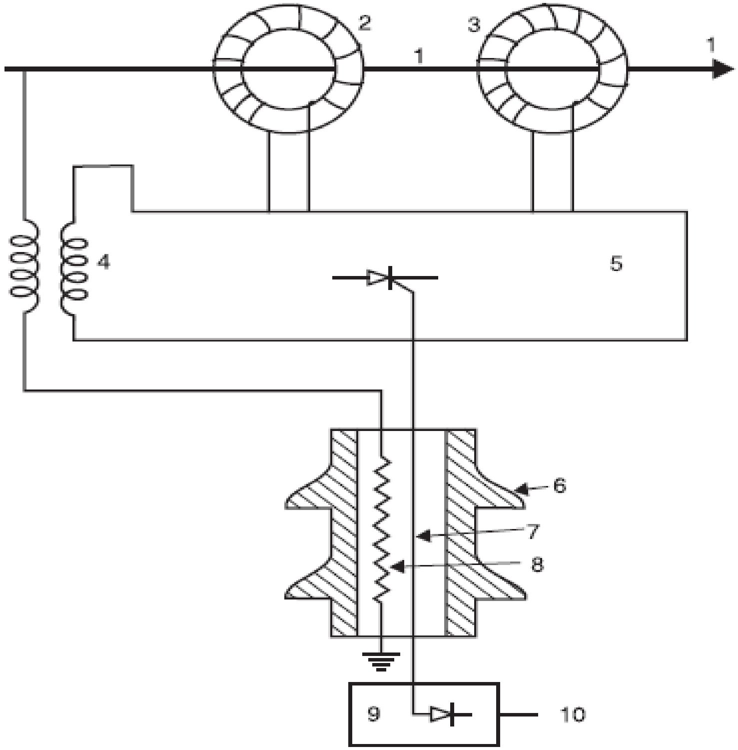


Fig. Current transformers and electro-optical system for high a.c. current measurements

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 photo detector 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.

Elements using Induction Effects

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:

$$v(t) = M \frac{di}{dt}$$

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 M is the number of turns of the coil, A the coil area and l_m its mean length, the mutual inductance is given by

$$M = \frac{\mu_0 NA}{l}$$

Usually an integrating circuit RC is employed as shown in Fig. 4.29 to obtain the output voltage proportional to the current to be measured. The output voltage is given by

$$v_0(t) = \frac{1}{RC}\int_0^t v(t)dt = \frac{1}{RC}\int M\frac{di}{dt}\,.\,dt = \frac{M}{RC}\int di = \frac{M}{RC}i(t)$$

or

$$v(t) = \frac{RC}{M}v_0(t)$$

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.

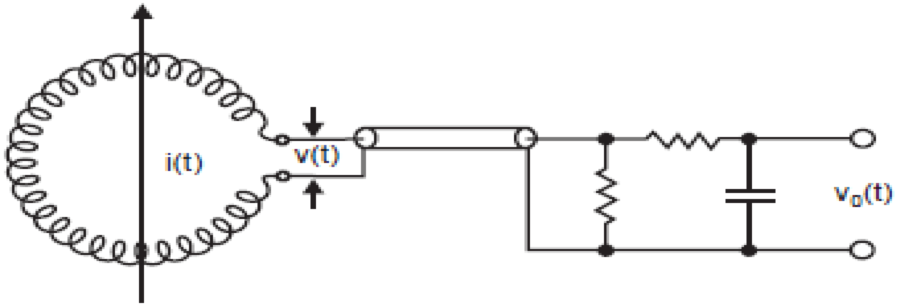


Fig. Rogowski coil for high impulse current measurements

Faraday Generator or Magneto Optic Method

These methods of current measurement use the rotation of the plane of polarisation in materials by the magnetic field which is proportional to the current (Faraday effect). When a linearly polarised light

beam passes through a transparent crystal in the presence of a magnetic field, the plane of polarisation of the light beam undergoes relation. The angle of rotation is given by

$\theta = \alpha Bl$

where α = A constant of the cyrstal which is a function of the wave length of the light.

B = Magnetic flux density due to the current to be measured in this case.

l = Length of the crystal.

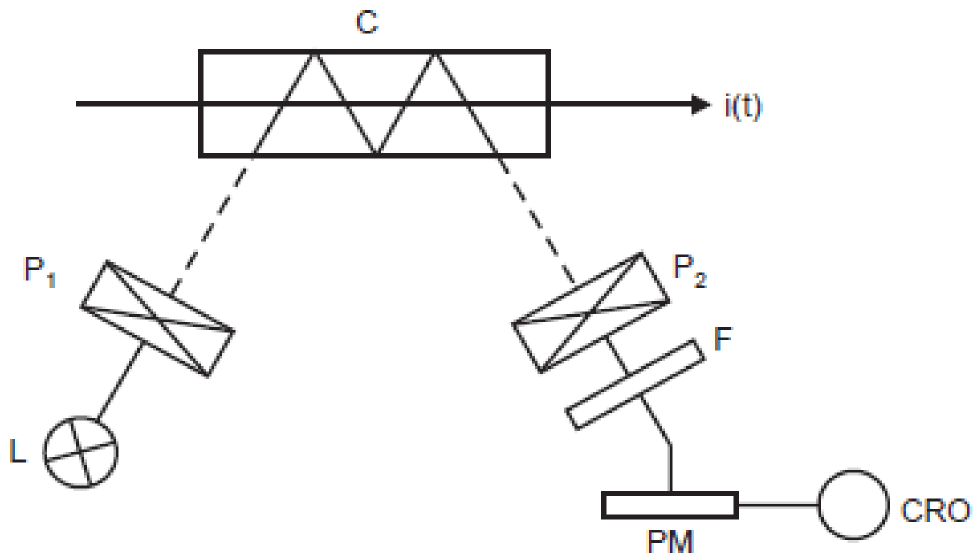


Fig. 4.30 Magneto-optical method

Fig. shows a schematic diagram of Magneto-optic method. Crystal *C* is placed parallel to the magnetic field produced by the current to be measured. A beam of light from a stabilised light source is made incident on the crystal *C* after it is passed through the polariser P_1. The light beam undergoes rotation of its plane of polarisation. After the beam passes through the analyser P_2, the beam is focussed on a photomultiplier, the output of which is fed to a CRO. The filter *F* allows only the monochromatic light to pass through it. Photoluminescent diodes too, the momentary light emission of which is proportional to the current flowing through them, can be used for current measurement. The following are the advantages of the method (*i*) It provides isolation of the measuring set up from the main current circuit. (*ii*) It is insensitive to overloading. (*iii*) As the signal transmission is through an optical system no insulation problem is faced. However, this device does not operate for d.c. current.