MODULE-3: MEASUREMENT OF HIGH VOLTAGE AND CURRENT

Syllabus

3.1 Measurement of High Direct Current Voltages
3.2 Measurement of High AC and Impulse Voltages
3.3 Measurement of High Currents – Direct, Alternating and Impulse ,Cathode Ray Oscillographs for Impulse Voltage and Current Measurements

Course Objectives

To discuss generation of high voltages and currents and their measurement

3.1 Measurement of High Direct Current and A.C Voltages

High voltage Measurement Techniques

Type of voltage	Method or technique
(a) d.c. voltages	*(i)* Series resistance microammeter
	(ii) Resistance potential divider
	(iii) Generating voltmeters
	(iv) Sphere and other spark gaps
(b) a.c. voltages	*(i)* Series impedance ammeters
(power frequency)	*(ii)* Potential dividers (resistance or capacitance type)
	(iii) Potential transformers (electromagnetic or CVT)
	(iv) Electrostatic voltmeters
	(v) Sphere gaps
(c) a.c. high frequency voltages, impulse voltages, and other rapidly changing voltages	*(i)* Potential dividers with a cathode ray oscillograph (resistive or capacitive dividers)
	(ii) Peak voltmeters
	(iii) Sphere gaps

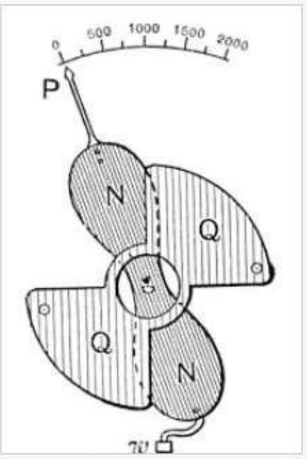
High Current Measurement Techniques

Type of current	Device or technique
(a) Direct currents	(i) Resistive shunts with milliammeter
	(ii) Hall effect generators
	(iii) Magnetic links
(b) Alternating currents (Power frequency)	(i) Resistive shunts
	(ii) Electromagnetic current transformers
(c) High frequency a.c., impulse and rapidly changing currents	(i) Resistive shunts
	(ii) Magnetic potentiometers or Rogowski coils
	(iii) Magnetic links
	(iv) Hall effect generators

3.1.1 Electrostatic voltmeter

Principle of Operation

1. **Electrostatic voltmeter** can be referred to an ***electrostatic charge meter.***
2. Electrostatic Voltmeter to measure large electrical potential. (*Direct method of measuring HV*)
3. It can accurately measure *surface potential (voltage)* on materials without making physical contact.
4. Electrostatic voltmeter utilizes the *attraction force* between *two charged surfaces.*
5. Attraction between 2 charged surface create a *deflection of a pointer* directly calibrated in *volts.*
6. *Attraction Force* is proportional to the *square of the applied voltage.*
7. The measurement can be made for *AC or DC voltages*.
8. When one of the electrodes is free to move, the force on the plate can be measured by *controlling it by a spring or balancing* it with a *counterweight.*
9. Electrostatic voltmeter is designed to measure high potential differences; typically from a few hundred to many thousands volts.



Electrostatic voltmeter operation

10. Electrostatic voltmeter utilizes the attraction force between two charged surfaces to create a deflection of a pointer directly calibrated in volts.
11. The pivoted sector NN is attracted to the fixed sector QQ

12. The moving sector indicating the voltage by the pointer P and is counterbalanced by the small weight w.
13. Damping technique is Air friction damping.

In electrostatic fields, the attractive force between the electrodes of a parallel plate condenser is given by:

$$F = \frac{1}{2}\varepsilon_0 A\left(\frac{V}{s}\right)^2$$

$V =$ applied voltage between plates,
$C =$ capacitance between the plates,
$A =$ area of cross-section of the plates,
$s =$ separation between the plates,
$\varepsilon_0 =$ permittivity of the medium (air or free space)
$W_s =$ work done in displacing a plate

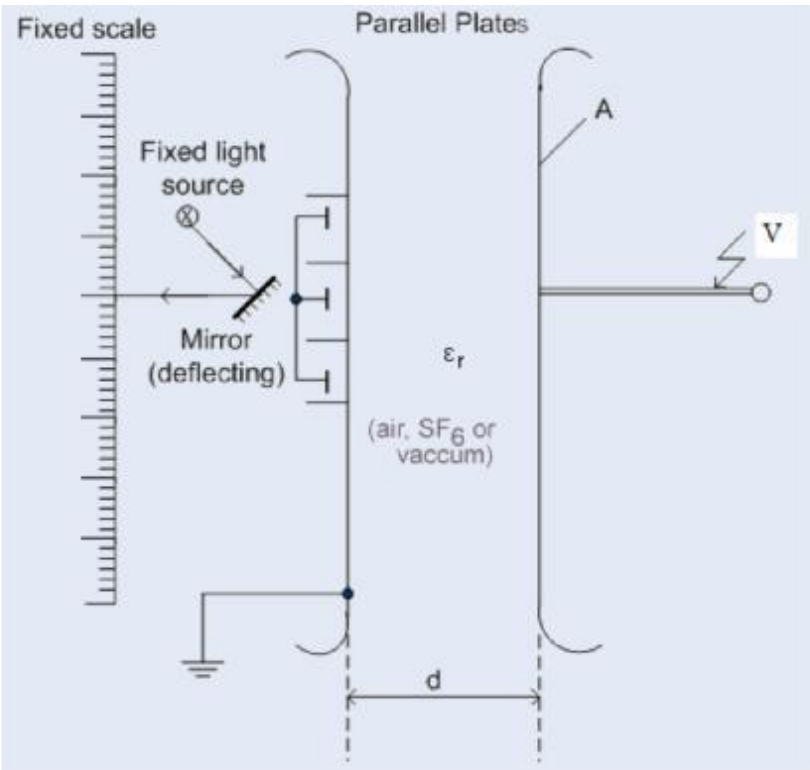
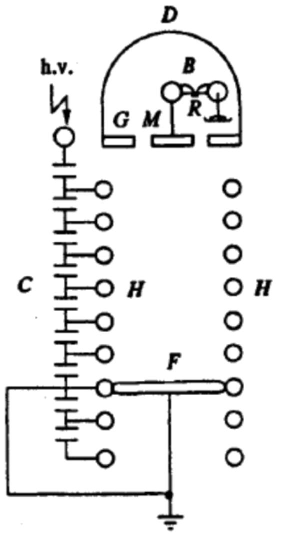
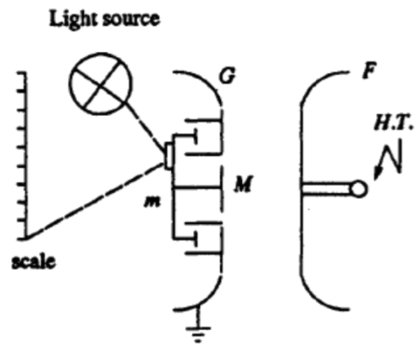


Fig: Schematic Diagram



Absolute electrostatic voltmeter



m — mirror
Light beam arrangement

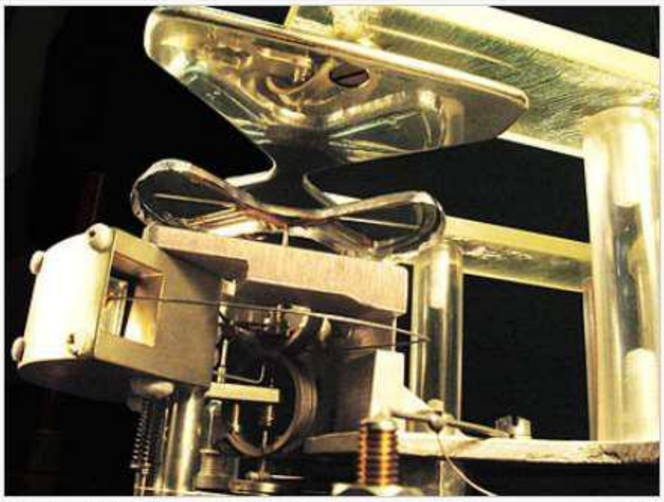
M — Mounting plate
G — Guard plate
F — Fixed plate
H — Guard hoops or rings

B — Balance
C — Capacitance divider
D — Dome
R — Balancing weight

Fig: Constructional Details

Construction

1. Electrostatic voltmeters are made with *parallel plate configuration* using *guard rings* to avoid corona and maintain constant potential.
2. An absolute voltmeter is made by balancing the plate with a counter weight and is calibrated in terms of a small weight.
3. The electrostatic voltmeters have *a small capacitance (5 to 50 pF)*
4. High insulation resistance *(*above 1000 ohm*).*
5. They are considered as devices with *high input impedance.*
6. An upper frequency limit of about *one MHz* is achieved in careful designs.
7. The *accuracy* for AC voltage measurements is better than DC voltage measurements.
8. It consists of parallel plane disc type electrodes separated by a small distance.
9. The moving electrode is surrounded by a fixed guard ring to make the field uniform in the central region.
10. In order to measure the given voltage with *precision*, the *disc diameter is to be increased*, and the *gap distance is to be made less*
11. The *balancing weight* gives controlling torque.
12. Electrostatic voltmeters are constructed in an enclosed structure containing compressed air or SF6 or carbon dioxide or nitrogen.
13. The *gas pressure* may be in the order of *15atm and* Working stress= 100kV/cm



Electrostatic voltmeter mechanism

Advantages

1. Active power loss is negligibly small
2. Low loading effect
3. Voltage up to 600kV can be measured

Limitations

1. The measurement of *voltage lower than 50V* is not possible because force become too small.
2. For constant distance 's', **$F \propto V^2$**, the sensitivity is small. This can be overcome by varying the gap distance d in appropriate steps.

3.2 Measurement of HVAC Voltages : Chubb and Fortescue method for HV AC measurement

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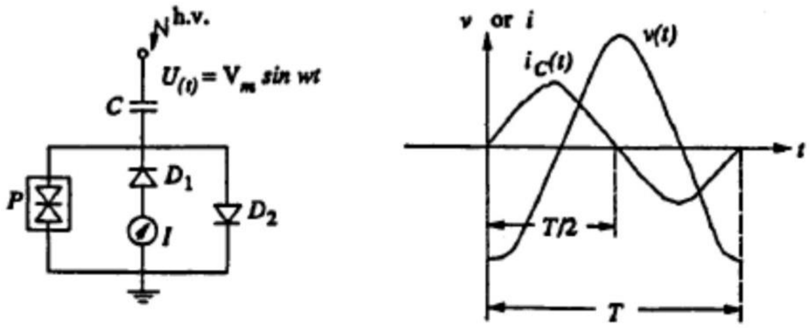
1. It is a simple and accurate method for the **peak measurement of AC voltage.**
2. It can be defined as peak voltmeter method.
3. Suggested by Chubb and Fortescue in 1913.
4. *Peak value* of instrument is required for HV measurement.
5. Peak value of an *AC waveform* is more important.
6. When the waveform is not sinusoidal, **rms value of the voltage multiplied by square root of 2 is not correct.**
7. Hence a *separate peak value* instrument is desirable in high voltage applications.



Peak voltmeter with a series capacitor

C — Capacitor
D_1, D_2 — Diodes
P — Protective device
I — Indicating meter (rectified current indicated)

$v(t)$ — Voltage waveform
$I_c(t)$ — Capacitor current waveform
T — Period

8. When a capacitor is connected to a sinusoidal voltage source, the *charging current* is generated.
9. The meter reading is proportional to the peak value of the value ***Vm***.

$$V_m = \frac{I}{2\pi f C}$$

where *'I'* is the dc current read by the meter and C is the capacitance of the capacitor.

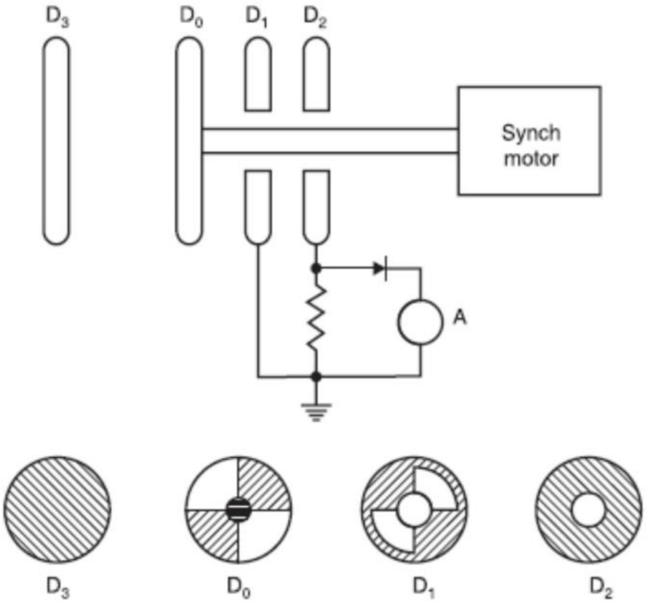
This method is known as the *__Chubb-Frotscue method__* __for peak voltage measurement.__

3.2.1 Generating voltmeter

1. **"A generating voltmeter is a *variable capacitor electrostatic voltage generator* which generates current proportional to the applied external voltage"**

2. The device is driven by an ***__external synchronous or constant speed motor__*** and does not absorb power or energy from the voltage measuring source. i.e *no loading effect*.
3. Generating volt meter can measure loss free AC voltage.
4. Generating voltmeters are *high impedance devices.*
5. No direct connection to the high voltage.

Construction



Schematic diagram of generating voltmeter

- **Fig. shows a schematic diagram of a generating voltmeter which employs rotating vanes for variation of capacitance.**

1. 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.***

2. The **rotor *D_0*** *is* driven at a suitable constant speed by a synchronous motor.

3. Rotor vanes of D_0 cause periodic change in capacitance between the insulated disc D_2 and the high voltage electrode D_3.

4. Number and shape of vanes are so designed that a suitable variation of capacitance (sinusoidal or linear) is achieved.

5. The AC 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.

6. Generating voltmeters are linear scale instruments and applicable over a wide range of voltages.

7. The sensitivity can be increased by increasing the area of the pick up electrode and by using amplifier circuits

Principle of operation

1. We have charge stored in the capacitor

$$q = CV.$$

2. If the capacitance of the capacitor varies with time when connected to the source of voltage *V, the current through the capacitor*

$$i = \frac{dq}{dt} = V\frac{dC}{dt} + C\frac{dV}{dt}$$

For d.c. voltages $dV/dt = 0$. Hence,

$$i = \frac{dq}{dt} = V\frac{dC}{dt}$$

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

$$C = C_0 + C_m \sin \omega t$$

the current i is

$$i = i_m \cos t\, \omega t$$

where

$$i_m = V C_m \omega$$

(i_m is the peak value of the current). The rms value of the current is given by:

$$i_{rms} = \frac{VC_m\omega}{\sqrt{2}}$$

3. For a constant angular frequency, the ***current* is proportional to the *applied voltage V*.**
4. More often, the generated current is rectified and measured by a *moving coil meter*.
5. Generating voltmeter can be used for **AC *voltage measurements*** also provided the *angular frequency* is the same or equal to half that of the supply frequency.

Advantages of Generating Voltmeters

1. No source loading by the meter
2. No direct connection to high voltage electrode
3. scale is linear and extension of range is easy
4. A very convenient instrument for electrostatic devices such as **Van de Graff generator** and particle accelerators.

Limitations of Generating Voltmeters

1. They require calibration
2. Careful construction is needed and is a cumbersome instrument requiring an auxiliary drive
3. Disturbance in position and mounting of the electrodes make the calibration invalid.

Numerical

Example : A generating voltmeter has to be designed so that it can have a range from 20 to 200 kV d.c. If the indicating meter reads a minimum current of 2 μA and maximum current of 25 μA, what should the capacitance of the generating voltmeter be ?

Solution:

Solution: Assume that the driving motor has a synchronous speed of 1500 rpm.

$$I_{rms} = \frac{VC_m}{\sqrt{2}}\,\omega$$

where, V = applied voltage,

C_m = capacitance of the meter, and

ω = angular speed of the drive

Substituting,

$$2 \times 10^{-6} = \frac{20 \times 10^3 \times C_m}{\sqrt{2}} \times \frac{1500}{60} \times 2\pi$$

$$\therefore \quad C_m = 0.9 \text{ p.F}$$

At $$200 \text{ kV}, I_{rms} = \frac{200 \times 10^3 \times 0.9 \times 10^{-12} \times 1500}{\sqrt{2} \times 60} 2\pi$$

$$= 20.0\ \mu\text{A}$$

Measurement of Ripple Voltage In D.C Systems

Measurement of Ripple with CRO

1. The detailed circuit arrangement used for this purpose is shown in Fig.. Here, the capacitance 'C' is rated for the peak voltage.
2. It is important that the switch ·S' be closed when the *CRO* is connected to the source so that the *CRO* input terminal does not receive any high voltage signal while 'C" is being charged.
3. C should be larger than the capacitance of the cable and the input capacitance of the CRO, taken together.

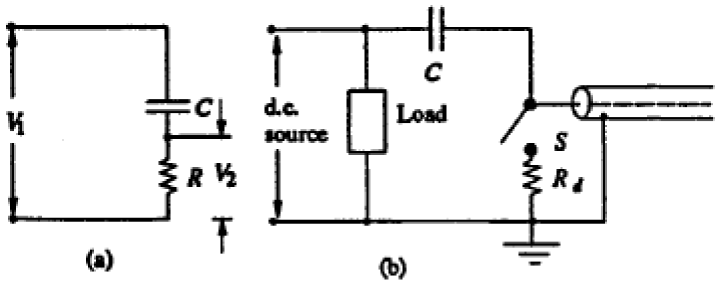


Fig. Circuit arrangement for the measurement of ripple voltage

3.2.2 Series resistance micro ammeter

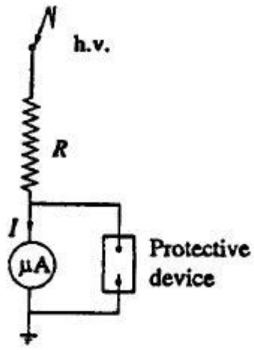
1. **A large value of resistance (few hundreds of mega ohms) is connected in series with uA.**
2. **Protective device (Zener diode) connected across the uA.**

Need for protective device:

1. If R fails, heavy current will flow through µA
2. To divert protective device is used

Operation of series resistance micro ammeter

1. **"R "should be high**
2. **High DC voltage is applied**
3. **Voltage drop across the resistance**
4. **The current flowing through the resistance 'R' is measured in µA.**



Series resistance micrometer

5. *The resistance is constructed from a* *large no. of wire wound resistors in series.*
6. Voltage V=IR
7. Drop in Ammeter is negligible
8. R should be chosen such that 1 to 10 uA is allowed for full scale deflection **500 kV** can be measured
9. **Accuracy : 20%**

Construction

1. The voltage drop in the meter is negligible, as the impedance of the meter is only few ohms compared to few hundred mega-ohms of the series resistance R.
2. A protective device like a paper gap, a neon glow tube, or a zener diode with a suitable series resistance is connected across the meter as a protection against high voltages in case the series resistance R fails or flashes over.
3. The ohmic value of the series resistance R is chosen such that a current of one to ten microamperes is allowed for full-scale deflection.
4. The voltage drop in each resistor element is chosen to avoid surface flashovers and discharges.
5. The material for resistive elements is usually a carbon-alloy with temperature coefficient less than 10-4X C. Carbon and other metallic film resistors are also used. A resistance chain built with ±1% carbon resistors located in an airtight transformer oil filled P.V.C. tube, for 100 kV operation had very good temperature stability.

Functions of series resistance

i) Limit the breakdown current

ii) To suppress unwanted oscillations

The limitations in the series resistance design are:

1. power dissipation and source loading,

2. temperature effects and long time stability,
3. voltage dependence of resistive elements, and
4. Sensitivity to mechanical stresses.

3.2.3 Standard Sphere Gap Measurement

a) Importance of sphere gap measurement

1. Peak value of voltage causes dielectric breakdown.
2. ***A sphere gap* can be used for measurement of the *peak value* of the voltage if the *gap distance* is known.**
3. Sphere gap measurement is one of the standard method of measuring *peak value of high voltage **DC, AC and impulse voltage.***
4. It is used for checking voltmeters and other voltage measuring devices used in HV testing circuits.
5. Two types of sphere gap arrangement
    a. **Horizontal sphere gap arrangement**
    b. **Vertical sphere gap arrangement**

b) Construction

Standard diameter of the spheres are *2, 5, 6.25, 10, 12.5, 15, 25, 50, 75,100, 150 and 200cm.*

a. Horizontal arrangement is usually is preferred for sphere diameter **d<50cm** and it is suitable for **low voltage range.**
b. One of the sphere is static and other is movable (adjustable).
c. Impulse voltage which has wave front time at least 1µs & wave tail time of 5µs can be measured using sphere gap measurement.

a. Horizontal arrangement of sphere gap

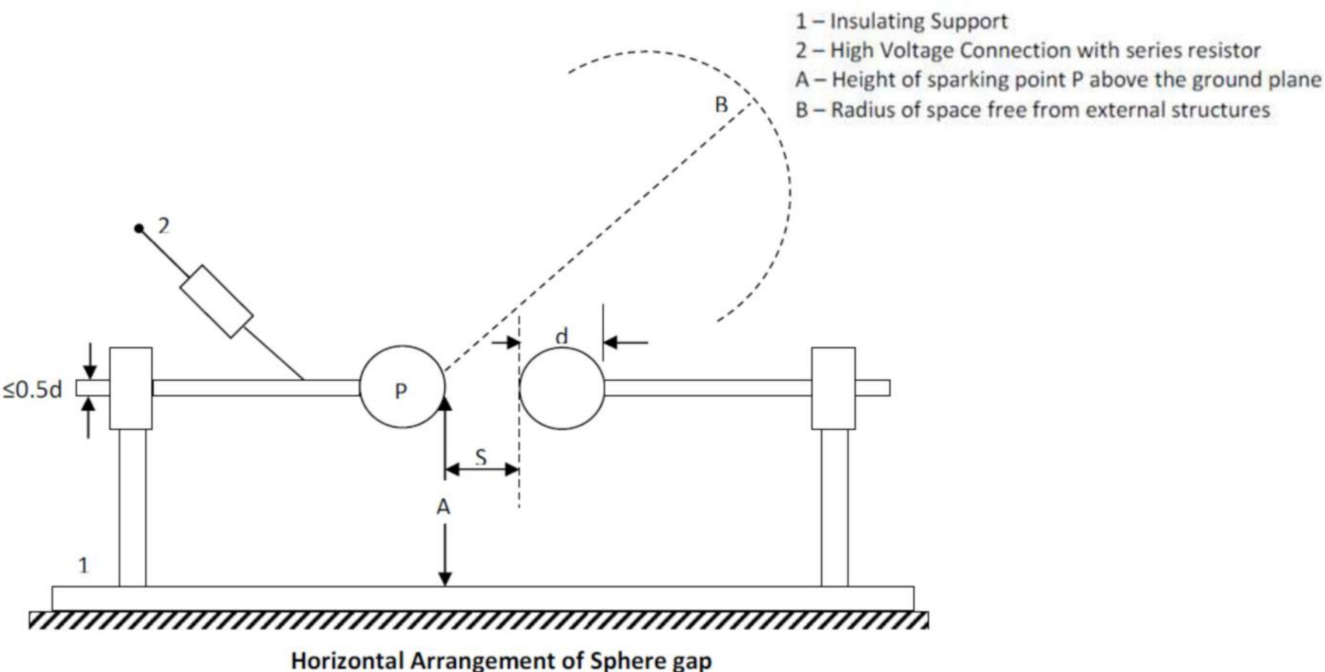
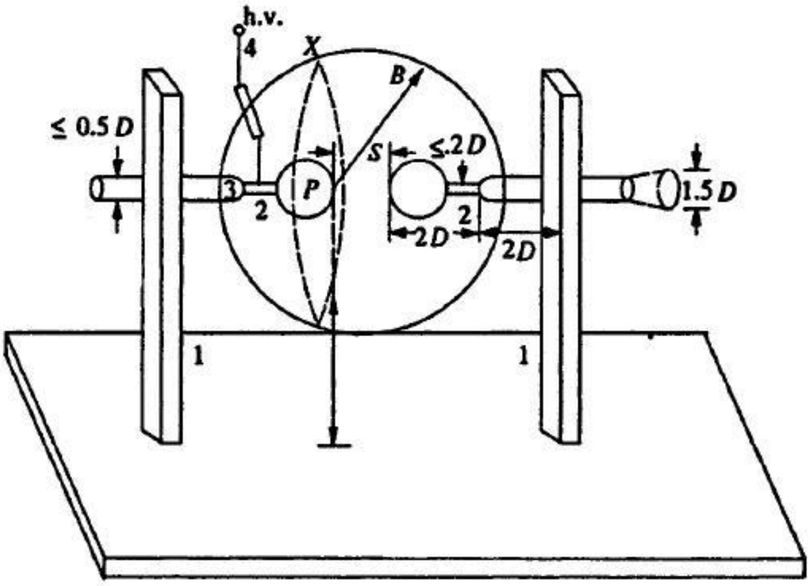
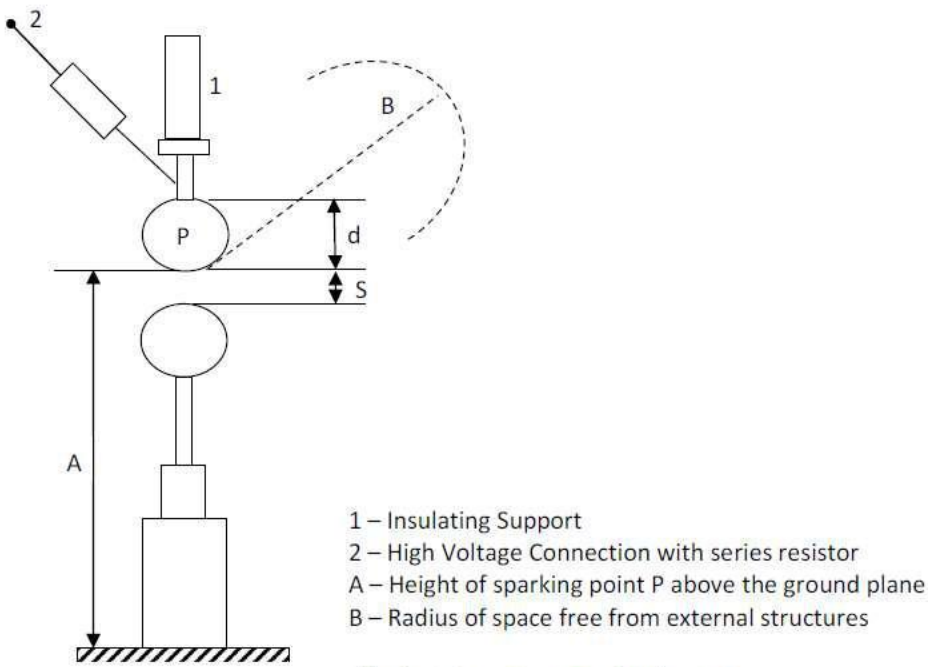


Fig: Horizontal arrangement of sphere gap



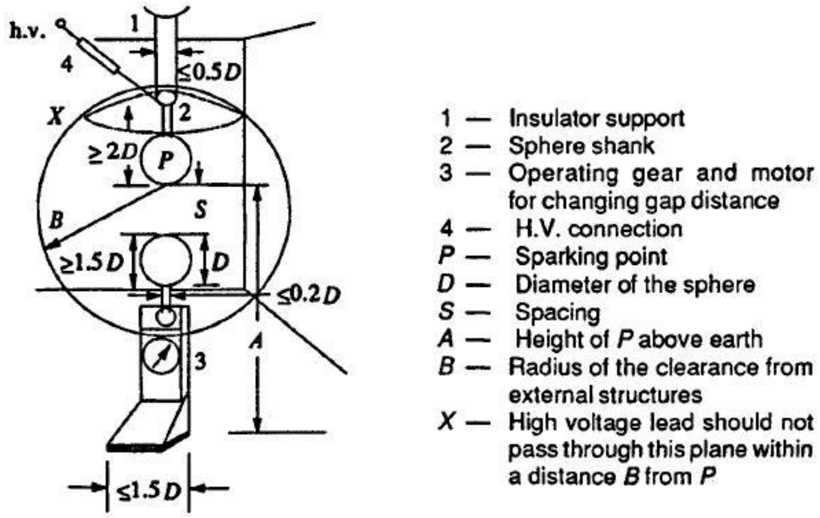
Horizontal arrangement of sphere gap

b. Vertical arrangement of sphere gap



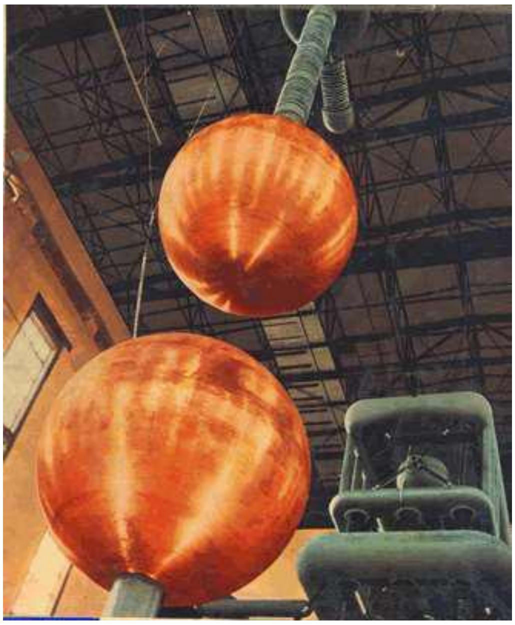
Vertical Arrangement of Sphere gap

Construction



Vertical arrangement of sphere gap

Sphere gap for voltage measurement



1. When the electric field across the gap exceeds static breakdown strength of gap, it results complete **breakdown of gaseous gap.**
2. Spheres having equal diameters and it is made of ***Cu or Al.***
3. The distance between two spheres are less than the diameter of spheres.
4. ***Sphere gaps can be arranged* either**

   (i) *Vertically* with lower sphere grounded,

   (ii) Horizontally with both spheres connected to the source voltage or one sphere grounded.

5. The spheres are carefully designed and fabricated so that their surfaces are smooth and the curvature is uniform.
6. Spacing S between them gives a measure of the *spark over voltage*.
7. **A** ***series resistance*** is usually connected between the source and the sphere gap to
   (i) Limit the breakdown current, and
   (ii) to suppress unwanted oscillations in the source voltage when breakdown occurs (in case of impulse voltages).
8. The value of the series resistance may vary from ***100 to 1000 kilo ohms*** for AC or AC voltages and not more than ***500 ohm*** in the case of impulse voltages.

Factors affecting the measurements

1. ***Nearby earthed objects :*** Changes in breakdown strength
2. ***Atmospheric conditions and humidity :*** Breakdown voltage of a spark gap depends on density.
3. ***Irradiation***
4. ***Polarity and rise time of voltage waveforms:*** Breakdown voltage for positive & negative polarity impulses are different.
5. ***Influence of dust particle:*** Presence of dust Particle cause erratic breakdown.

(i) Effect of nearby earthed objects

The effect of nearby earthed objects was investigated by Kuffel[14] by enclosing the earthed sphere inside an earthed cylinder. It was observed that the sparkover voltage is reduced. The reduction was observed to be

$$\Delta V = m \log (B/D) + C$$

where, ΔV = percentage reduction,
B = diameter of earthed enclosing cylinder,
D = diameter of the spheres,
S = spacing, and m and C are constants.

The reduction was less than 2% for $S/D \leq 0.5$ and $B/D \geq 0.8$. Even for $S/D \approx 1.0$ and $B/D \geq 1.0$ the reduction was only 3%. Hence, if the specifications regarding the clearances are closely observed the error is within the tolerances and accuracy specified. The variation of breakdown voltage with A/D ratio is given in Figs. 7.19a and b for a 50 cm sphere gap. The reduction in voltage is within the accuracy limits, if S/D is kept less than 0.6. A in the above ratio A/D is the distance from sparking point to horizontal ground plane (also shown in Fig. 7.19).

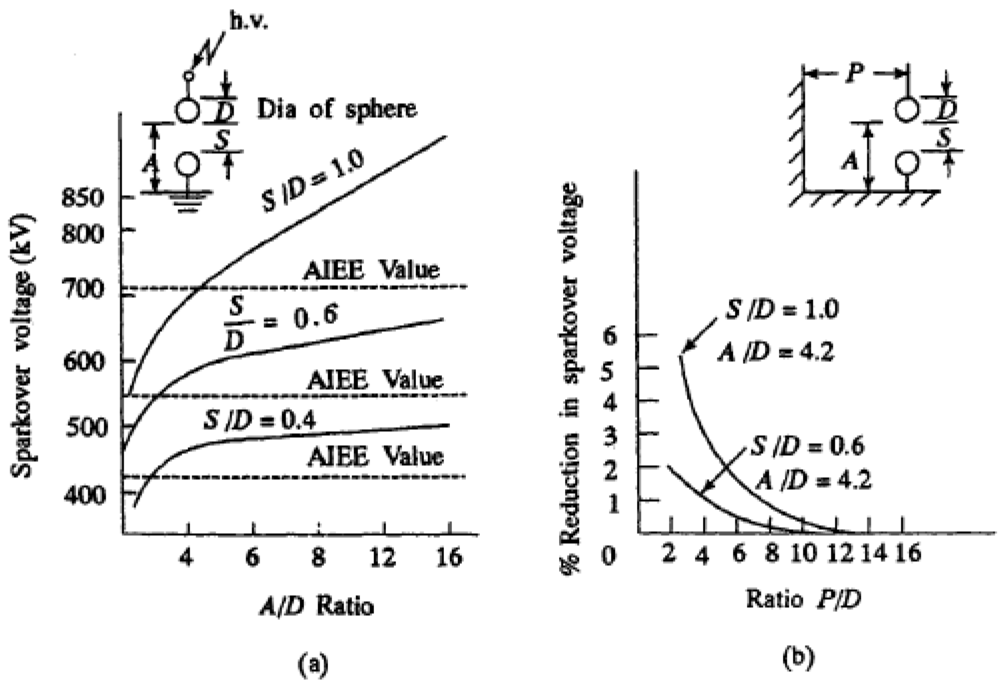


Fig. 7.19 Influence of ground planes on sparkover voltage

(ii) Effect of atmospheric conditions

The sparkover voltage of a spark gap depends on the air density which varies with the changes in both temperature and pressure. If the sparkover voltage is V under test conditions of temperature T and pressure p torr and if the sparkover voltage is V_0 under standard conditions of temperature $T = 20°C$ and pressure $p = 760$ torr, then

$$V = kV_0$$

where k is a function of the air density factor d, given by

$$d = \frac{p}{760}\left(\frac{293}{273+T}\right)$$

The relationship between d and k is given in Table 7.6.

Table 7.6 Relation between Correction Factor k and Air Density Factor d

d	0.70	0.75	0.80	0.85	0.90	0.95	1.0	1.05	1.10	1.15
k	0.72	0.77	0.82	0.86	0.91	0.95	1.0	1.05	1.09	1.12

The sparkover voltage increases with humidity. The increase is about 2 to 3% over normal humidity range of 8 g/m^3 to 15 g/m^3.

(iii) Effect of Irradiation

Illumination of sphere gaps with ultra-violet or x-rays aids easy ionization in gaps. The effect of irradiation is pronounced for small gap spacings. A reduction of about 20% in sparkover voltage was observed for spacings of 0.1 D to 0.3 D for a 1.3 cm sphere gap with d.c. voltages. The reduction in sparkover voltage is less than 5% for gap spacings more than 1 cm, and for gap spacings of 2 cm or more it is about 1.5%. Hence, irradiation is necessary for smaller sphere gaps of gap spacing less than 1 cm for obtaining consistent values.

(iv) Effect of polarity and waveform

It has been observed that the sparkover voltages for positive and negative polarity impulses are different. Experimental investigation showed that for sphere gaps of 6.25 to 25 cm diameter, the difference between positive and negative d.c. voltages is not more than 1%. For smaller sphere gaps (2 cm diameter and less) the difference was about 8% between negative and positive impulses of 1/50 μ s waveform. Similarly, the wave front and wave tail durations also influence the breakdown voltage. For wave fronts of less than 0.5 μ s and wave tails less than 5 μ s the breakdown voltages are not consistent and hence the use of sphere gap is not recommended for voltage measurement in such cases.

Table Peak value of sparkover voltage in kV for a.c., d.c. voltages of either polarity, and for full negative standard impulse voltages (one sphere earthed) (a) and positive polarity impulse voltages and impulse voltages with long tails (b) at temperature: 25°C and pressure: 760 torr

Gap spacing (cm)	Sphere diameter (cm)															
	5		10		15		25		50		100		150		200	
	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B
0.5	17.4	17.4	16.9	16.8	16.9	16.9										
1.0	32.0	32.0	31.7	31.7	31.4	31.4	31.2	31.4								
1.5	44.7	45.5	44.7	45.1	44.7	45.1	44.7	44.7								
2.0	57.5	58.0	58.0	58.0	58.0	58.0	58.0	58.0								
2.5			71.5	71.5	71.5	71.5	71.5	71.5	71.5	71.5						
3.0			85.0	85.0	85.0	85.0	85.0	85.0	85.0	85.0						
3.5			95.5	96.0	97.0	97.0	97.0	97.0	97.0	97.0						
4.0			106.0	108.0	108.0	110.0	110.0	110.0	110.0	110.0						
5.0			(123.0)	(127.0)	127.0	132.0	135.0	136.0	136.0	136.0						
7.5					(181.0)	(187.0)	195.0	196.0	199.0	199.0						
10.0							257	268	259	259	262	262	262	262	262	262
12.5							277	294	315	317						
15.0							(309)	(331)	367	374	383	384	384	384	384	384
17.5							(336)	(362)	413	425						
20.0									452	472	500	500	500	500	500	500
25.0									520	545	605	610				
30.0									(575)	(610)	700	715	730	735	735	740
35.0									(725)	(755)	785	800				
40.0											862	885	940	950	960	965
45.0											925	965				
50.0											1000	1020	1110	1130	1160	1170
75.0											(1210)	(1260)	1420	1460	1510	1590
100.0															1870	1900

Table Clearances for Sphere Gaps

D (cm)	Value of A		Value of
	Max	Min	*B* (min)
up to 6.25	7 *D*	9 *D*	14*S*
10 to 15	6 *D*	8 D	12*S*
25	5 *D*	7 *D*	10*S*
50	4 *D*	6 D	8*S*
100	3.5 *D*	5 D	7*S*
150	3 *D*	4 D	6*S*
200	3 *D*	4 D	6*S*

A and *B* are clearances as shown in Figs. 7.18a and 7.18b.
D = diameter of the sphere; *S* = spacing of the gap; and $S/D \leq 0.5$.

MEASUREMENT OF HIGH A.C AND IMPULSE VOLTAGES

1. Measurement of high a.c. voltages employ conventional methods like **series impedance voltmeters, potential dividers, potential transformers, or electrostatic voltmeters.**
2. But their designs are different from those of low voltage meters, as the insulation design and source loading are the important criteria.
3. When only peak value measurement is needed, peak voltmeters and sphere gaps can be used. Often, **sphere gaps** are used for calibration purposes

Series Impedance Voltmeters

For power frequency a.c. measurements the series impedance may be a pure resistance or a reactance. Since resistances involve power losses, often a capacitor is preferred as a series reactance. Moreover, for high resistances, the variation of resistance with temperature is a problem, and the residual inductance of the resistance gives rise to an impedance different from its ohmic resistance. High resistance units for high voltages have stray capacitances and hence a unit resistance will have an equivalent circuit as shown in Fig. 7.7. At any frequency ω of the a.c. voltage, the impedance of the resistance R is

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

Fig. 7.7 Simplified lumped parameter equivalent circuit of a high ohmic resistance R

L — Residual inductance

C — Residual capacitance

If ωL and ωC are small compared to R,

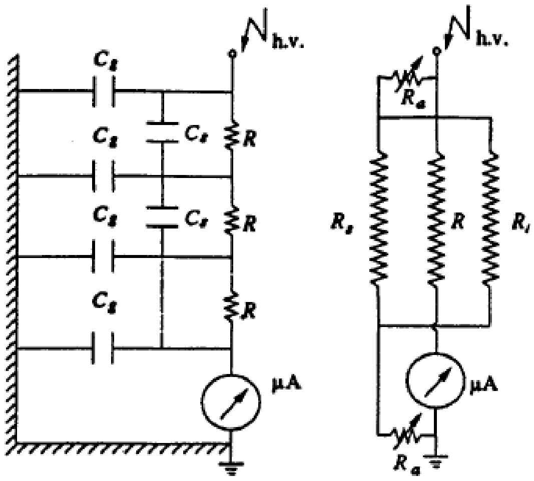
$$Z \approx R\left[1 + j\left(\frac{\omega L}{R} - \omega CR\right)\right]$$

and the total phase angle is

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

This can be made zero and independent of frequency, if

$$L/C = R^2$$



(a) Extended series resistance with inductance neglected

C_g — Stray capacitance to ground
C_s — Winding capacitance

(b) Series resistance with guard and tuning resistances

R — Series resistor
R_s — Guard resistor
R_a — Tuning resistor

Fig. Extended series resistance for high a.c. voltage measurements

Series Capacitance Voltmeter

To avoid the drawbacks pointed out earlier, a series capacitor is used instead of a resistor for a.c. high voltage measurements. The schematic diagram is shown in Fig. 7.9. The current I_c through the meter is:

$$I_c = j\,\omega\, CV$$

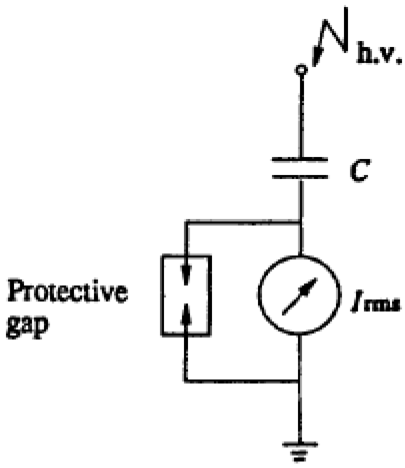


Fig. Series capacitance with a milliammeter for measurement of high a.c. voltages

where, C = capacitance of the series capacitor,

ω = angular frequency, and

V = applied a.c. voltage.

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

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

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

The currents due to these harmonics are

$I_1 = \omega\, CV_1$

$I_2 = 2\,\omega\, CV_2$, ..., and

$I_n = n\,\omega\, CV_n$

Hence, the resultant rms current is:

$$I = \omega\, C\,(V_1^2 + 4V_2^2 + \ldots + n^2V_n^2)^{1/2}$$

With a 10% fifth harmonic only, the current is 11.2% higher, and hence the error is 11.2% in the voltage measurement.

This method is not recommended when a.c. voltages are not pure sinusoidal waves but contain considerable harmonics.

Capacitance Potential Dividers and Capacitance Voltage Transformers

The errors due to harmonic voltages can be eliminated by the use of capacitive voltage dividers with an electrostatic voltmeter or a high impedance meter such as a V.T.V.M. If the meter is connected through a long cable, its capacitance has to be taken into account in calibration. Usually, a standard compressed air or gas condenser is used as C_1 (Fig. 7.10), and C_2 may be any large capacitor (mica, paper, or any low loss condenser). C_1 is a three terminal capacitor and is connected to C_2 through a shielded cable, and C_2 is completely shielded in a box to avoid stray capacitances. The applied voltage V_1 is given by

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

where C_m is the capacitance of the meter and the connecting cable and the leads and V_2 is the meter reading.

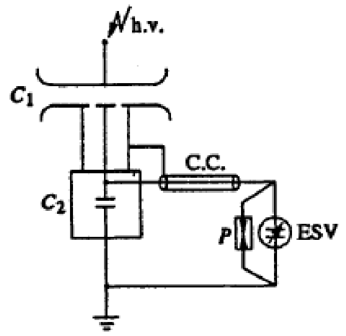
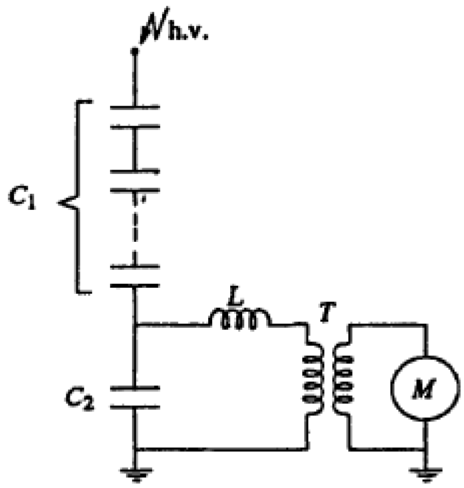


Fig. 7.10 Capacitance potential divider

C_1 — Standard compressed gas h.v. condenser
C_2 — Standard low voltage condenser
ESV — Electrostatic voltmeter
P — Protective gap
C.C. — Connecting cable

Capacitive Voltage Transformer



(a) Schematic representation

Capacitance divider with a suitable matching or isolating potential transformer tuned for resonance condition is often used in power systems for voltage measurements. This is often referred to as CVT. In contrast to simple capacitance divider which requires a high impedance meter like a V.T.V.M. or an electrostatic voltmeter, a CVT can be connected to a low impedance device like a wattmeter pressure coil or a relay coil. CVT can supply a load of a few VA. The schematic diagram of a CVT with its equivalent circuit is given in Fig. 7.11. C_1 is made of a few units of high voltage condensers, and the total capacitance will be around a few thousand picofarads as against a gas filled standard condenser of about 100 pF. A matching transformer is connected between the load or meter M and C_2. The transformer ratio is chosen on economic grounds, and the h.v. winding rating may be 10 to 30 kV with the l.v. winding rated from 100 to 500 V. The value of the tuning choke L is chosen to make the equivalent circuit of the CVT purely resistive or to bring resonance condition. This condition is satisfied when

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

where, L = inductance of the choke, and

L_T = equivalent inductance of the transformer referred to h.v. side.

The voltage V_2 (meter voltage) will be in phase with the input voltage V_1.

The advanges of a CVT are:

(*i*) simple design and easy installation,

(*ii*) can be used both as a voltage measuring device for meter and relaying purposes and also as a coupling condenser for power line carrier communication and relaying.

(*iii*) frequency independent voltage distribution along elements as against conventional magnetic potential transformers which require additional insulation design against surges, and

(*iv*) provides isolation between the high voltage terminal and low voltage metering.

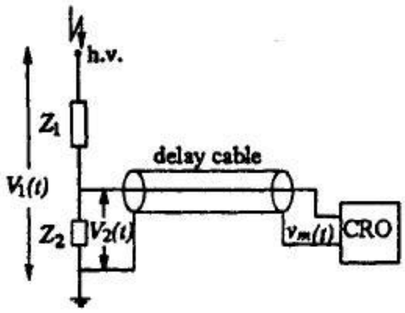
The disadvantages of a CVT are:

(*i*) the voltage ratio is susceptible to temperature variations, and

(*ii*) the problem of inducing ferro-resonance in power systems.

3.2.4 Potential dividers

1. Potential or voltage dividers useful for ***high voltage DC and AC measurement.***
2. Potential dividers are usually either *resistive* or *capacitive or mixed element type.*
3. The *low voltage arm* of the divider is usually *connected* to a *fast recording oscillograph* or a peak reading instrument through a *delay cable or a coaxial cable* .



Schematic diagram of a potential divider with a delay cable and oscilloscope

a. *Z1 is usually a resistor or a series of resistors in case* of a *resistance potential divider*.

b. *Z1 is usually* a single or a number of capacitors in case of a *capacitance divider*.

c. *Z1* can able to use the combination of *resistance & Capacitor in case of a mixed RC potential divider.*

d. *Z2* will be a resistor or a capacitor or an *R-C impedance depending upon the type of the* divider.

1. Resistance potential divider

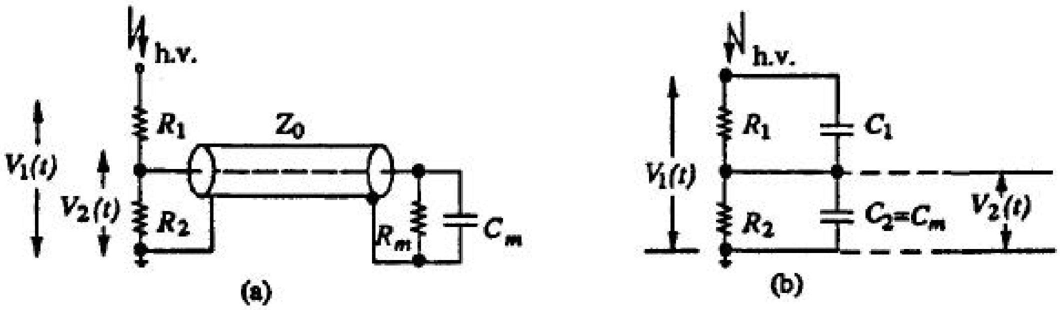
a. A simple resistance potential divider consists of two resistances *R1 and R2 in series. (R1>>R2)*

b. *Voltage ratio or attenuation factor is given by*

$$a = \frac{V_1(t)}{V_2(t)} = 1 + \frac{R_1}{R_2}$$

c. The *divider element R2,* in practice, is connected through the *coaxial cable* to the oscilloscope.

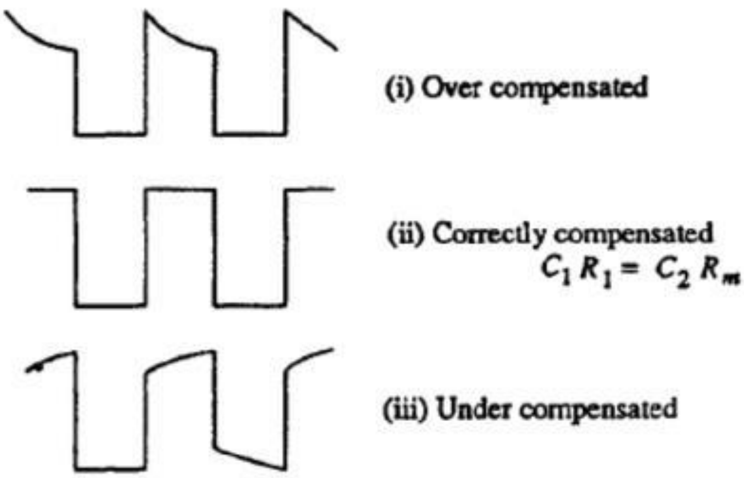
d. Sudden switching action causes Flash over voltage and that causes damage to divider circuit. In order to protect the dividers from flash over voltage, voltage controlled capacitors are used



Resistance potential divider with surge cable and oscilloscope terminations

Comepensated resistance potential divider

Resistance potential dividers



Output of compensated resistance voltage divider for different degrees of compensation

e. The cable will generally have a *surge impedance Z0*
f. Surge impedance will come in parallel with the oscilloscope input impedance *(Rm , Cm).*
g. *Rm will generally be greater than one Mega ohm* and *Cm may be* ***10 to 50 picofarads.***
h. For high frequency and impulse voltages, the ratio in the frequency domain will be given by

$$a = \frac{V_1}{V_2} = 1 + \frac{R_1}{(R_2/1 + j\omega R_2 C_m)}$$

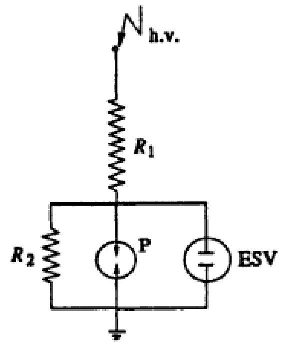


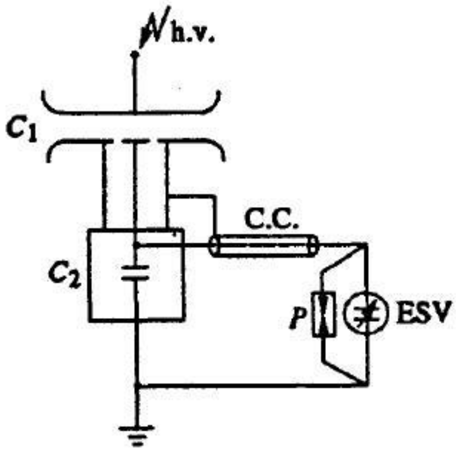
Fig Resistance potential divider with an electrostatic voltmeter

P — Protective device
ESV — Electrostatic volt-meter

1. A resistance potential divider with an electrostatic or high impedance voltmeter is shown in Fig.
2. The influence of temperature and voltage on the elements is eliminated in the voltage divider arrangement. The high voltage magnitude is given by ***[(R₁ + R2)/ R2]V2***, where *V2* is the d.c. voltage across the low voltage arm *R2*.
3. With sudden changes in voltage, such as switching operations, flashover of the test objects, or source short circuits, flashover or damage may occur to the divider elements due to the stray capacitance across the elements and due to ground capacitances.
4. To avoid these transient voltages, voltage controlling capacitors are connected across the elements.
5. A corona free termination is also necessary to avoid unnecessary discharges at high voltage ends.
6. Potential dividers are made with 0.05% accuracy up to 100 kV, with 0.1% accuracy up to 300 kV, and with better than **0.5% accuracy for 500 kV**

2. Capacitive potential divider

Impulse voltage can be measured by using capacitive potential dividers



C_1 - Standard Compressed Gas H.V. Condenser

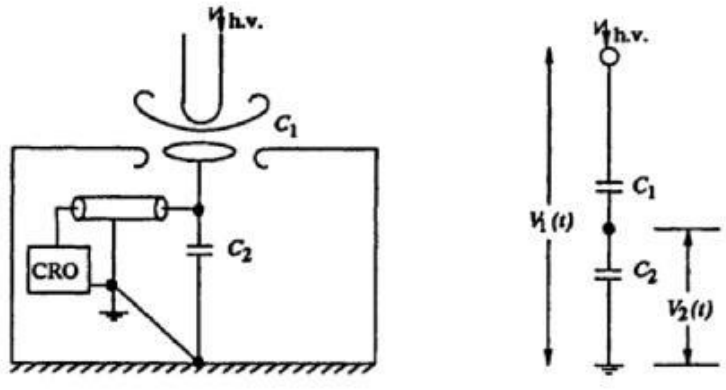
C_2 - Standard Low Voltage Condenser

ESV- Electrostatic Voltmeter P -Protective Gap C.C - Connecting Cable

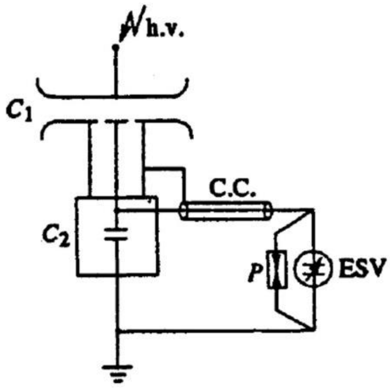
1. Harmonic Effects can be eliminated by use of Capacitive Potential Dividers (CPD) with Electro Static Voltmeter (ESV).
2. Gas filled condensers C_1 and C_2 are used as shown in figure.
3. C_1 is a three terminal capacitor, connected to C_2 by shielded cable.
4. C_2 is shielded to avoid stray capacitance
5. Capacitive potential divider can measure ***fast rising voltage & pulse and impulse voltage.***
6. Capacitance ratio *is* ***independent of frequency*****.**
7. Ratio of the divider (Attenuation factor) is given by

$$a = \frac{V_1(t)}{V_2(t)} = 1 + \frac{C_2}{C_1}$$

8. Capacitance *C1 is formed between the HV terminal of the source.*
9. **Suitable for measuring the impulse voltage up to** ***1 MV***
10. C1 is the *standard* ***compressed air or gas condenser- HV Capacitor.***
11. Value of *C2* is very high, C2 may be *mica capacitor, paper capacitor etc*
12. C1 is connected to C2 by using a **shield cable**
13. C2 is completely covered by using a box, for *avoiding stray capacitance.*
14. *Voltage can measure by using* ***VTVM*** **(Vacuum Tube Volt Meter) or ESV**- testing purpose for impulse voltage



Capacitance voltage divider for very high voltages and its electrical equivalent circuit



C_1 — Standard compressed gas h.v. condenser
C_2 — Standard low voltage condenser
ESV — Electrostatic voltmeter
P — Protective gap
C.C. — Connecting cable

Impulse voltage measurement by using capacitive

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

V1- Voltage to be measured

V2-Meter reading

C1-Standard compressed gas HV condenser

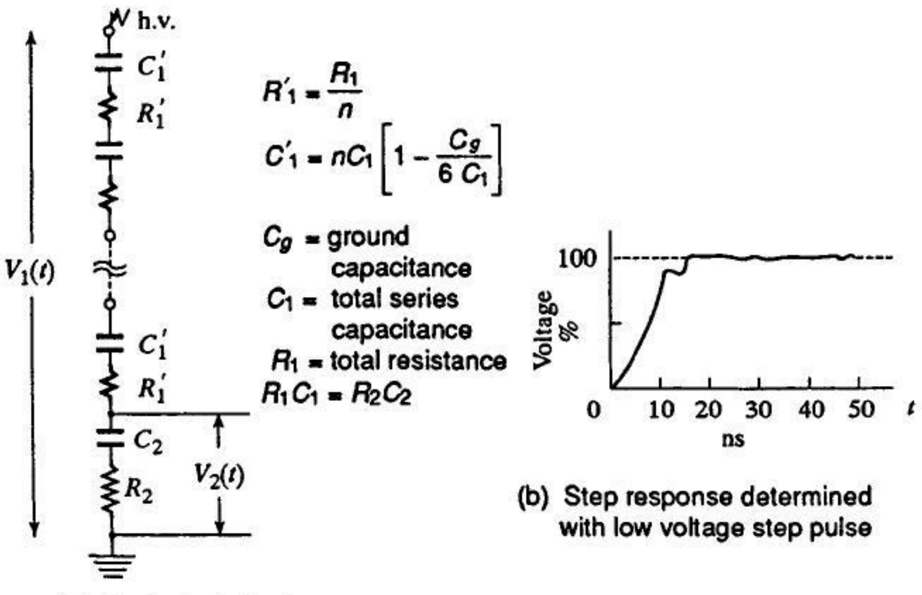
C2-Standard low voltage condenser Cm-Capacitance of the meter

Advantages

1. Loading on the source is negligible
2. Capacitance ratio independent of frequency

3. Mixed RC potential divider

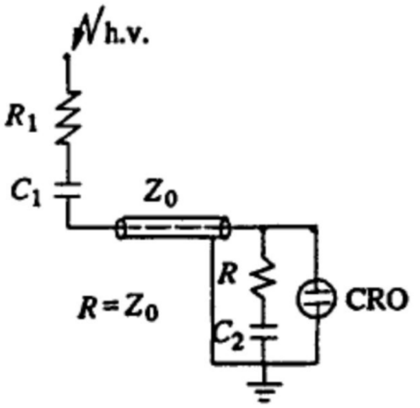
1. Mixed potential dividers use ***R-C elements in series or in parallel.***
2. *Improved step response*



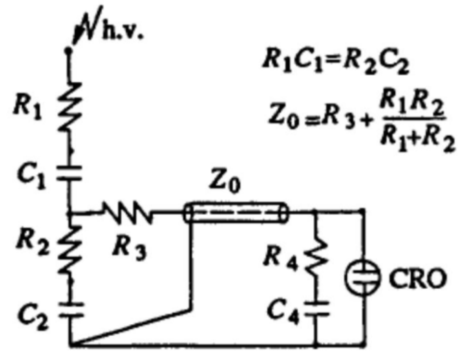
(a) Equivalent circuit

(b) Step response determined with low voltage step pulse

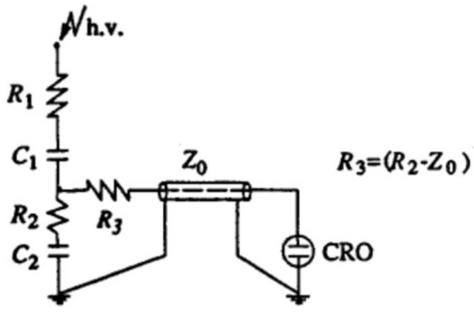
Equivalent circuit of a series R-C voltage divider and its step response



R-C series divider



Modified connection of R-C divider



Impedance matching with R-C divider

The following elements mainly constitute the different errors in the measurement:

1. *Residual inductance* in the elements
2. *Stray capacitance* occurring
   - **A.** ***between the elements,***
   - **B.** ***from sections and terminals of the elements to ground, and* (c) from the high voltage lead to the elements or sections**

3. The *impedance errors* due to *(a) connecting leads between the divider and the test objects, and (b) ground return leads and extraneous current in ground leads*
4. Parasitic oscillations due to lead and cable inductances and capacitance of high voltage terminal to ground.

Additional Information

Note1 -surge impedance

- The characteristic impedance or surge impedance of a *uniform transmission* line, usually written Z_0, is the *ratio of the amplitudes of voltage and current of a single wave propagating along the line.*

- That is, a wave travelling in one direction in the absence of reflections in the other direction.

- Characteristic impedance is determined by the *geometry and materials of the transmission line* and, for a uniform line, is *not dependent on its length*. The SI unit of characteristic impedance is the ohm.

Note 2-Parasitic capacitance

- In electrical circuits, parasitic capacitance, stray capacitance or, when relevant, self-capacitance, is an unavoidable and usually unwanted capacitance that exists between the parts of an electronic component or circuit simply because of their proximity to each other.

- All actual circuit elements such as inductors, diodes, and transistors have internal capacitance, which can cause their behavior to depart from that of 'ideal' circuit elements.

- Additionally, there is always non-zero capacitance between any two conductors; this can be significant at higher frequencies with closely spaced conductors, such as wires or printed circuit board traces.

3.3 MEASUREMENT OF HIGH DC , A.C AND IMPULSE CURRENTS

1. **In power system applications as well as in other scientific and technical fields, it is often necessary to determine the *amplitude and waveforms* of rapidly *varying high currents*.**
2. **High impulse currents occur in *lightning discharges, electrical arcs and post arc* phenomenon studies with *circuit breakers, and with electric discharge studies in plasma physics.***

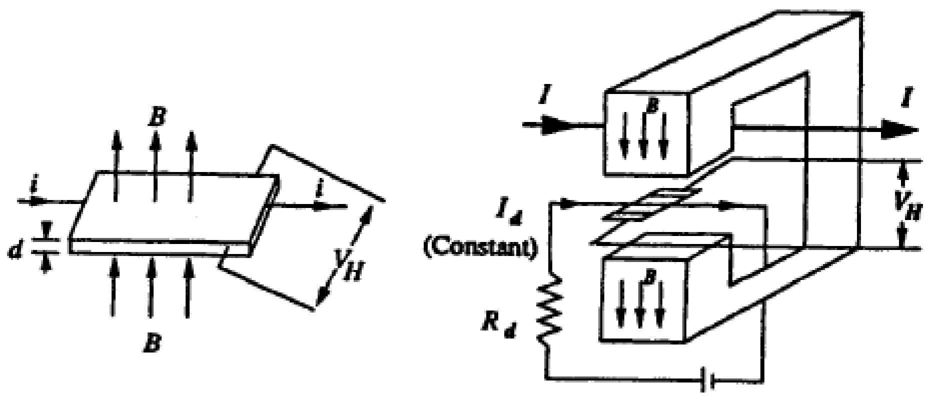
Hall Generators for d.c. Current Measurements

The principle of the "Hall effect" is made use of in measuring very high direct currents. If an electric current flows through a metal plate located in a magnetic field perpendicular to it, Lorenz forces will deflect the electrons in the metal structure in a direction normal to the direction of both the current and the magnetic field. The charge displacement generates an emf in the normal direction, called the "Hall voltage". The Hall voltage is proportional to the current i, the magnetic flux density B, and the reciprocal of the plate thickness d; the proportionality constant R is called the "Hall coefficient".

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

For metals the Hall coefficient is very small, and hence semi-conductor materials are used for which the Hall coefficient is high.

In large current measurements, the current carrying conductor is surrounded by an iron cored magnetic circuit, so that the magnetic field intensity $H = (I/\delta)$ is produced in a small air gap in the core. The Hall element is placed in the air gap (of thickness δ), and a small constant d.c. current is passed through the element. The schematic arrangement is shown in Fig. 7.43. The voltage developed across the Hall element in the normal direction is proportional to the d.c. current I. It may be noted that the Hall coefficient R depends on the temperature and the high magnetic field strengths, and suitable compensation has to be provided when used for measurement of very high currents.



$V_H = R \cdot \frac{Bi}{d}$; R = Hall coefficient

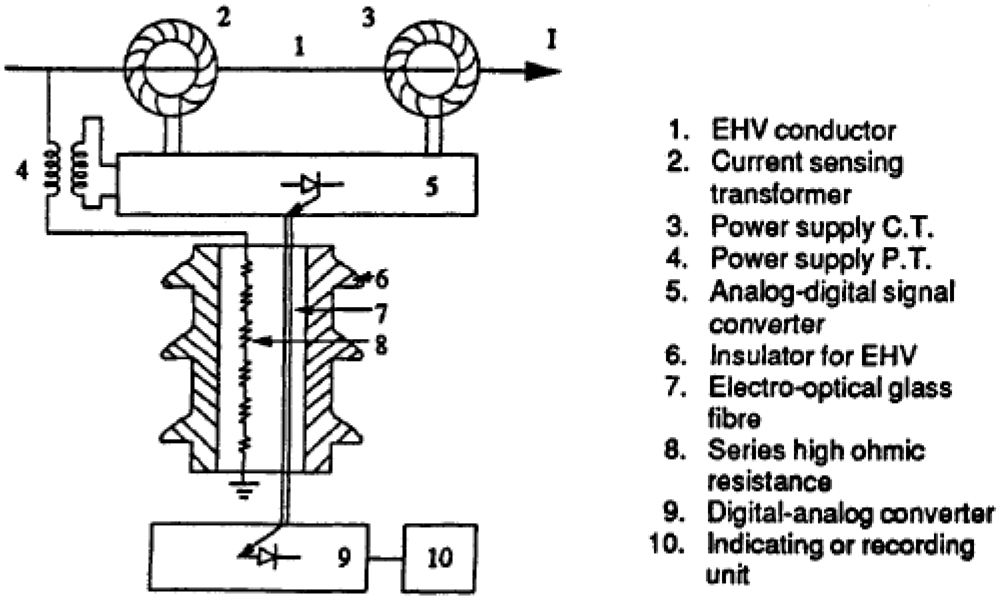
(a) Hall effect

(b) Hall generator

Fig. 7.43 Hall generator for measuring high d.c. currents

Measurement of High Power Frequency Alternating Currents

Measurement of power frequency currents are normally done using current transformers only, as use of current shunts involves unnecessary power loss. Also the current transformers provide electrical isolation from high voltage circuits in power systems. Current transformers used for extra high voltage (EHV) systems are quite different from the conventional designs as they have to be kept at very high voltages from the ground. A new scheme of current transformer measurements introducing



Current transformer with electro-optical signal converter for EHV systems

electro-optical technique is described in Fig.. A voltage signal proportional to the measuring current is generated and is transmitted to the ground side through an 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.

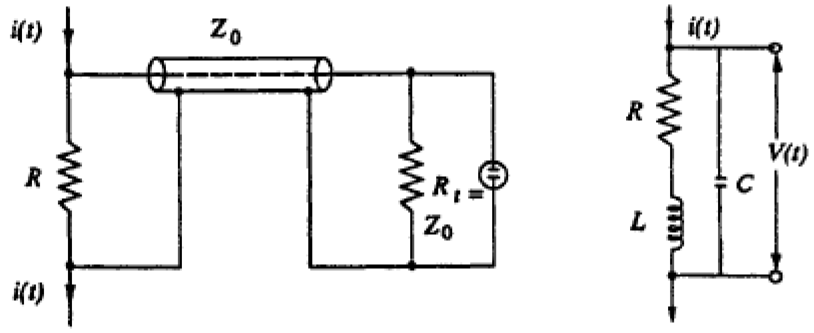
Measurement of High Frequency and Impulse Currents

High impulse currents occur in lightning discharges, electrical arcs and post arc phenomenon studies with circuit breakers, and with electric discharge studies in plasma physics. The current amplitudes may range from a few amperes to few hundred kiloamperes. The rate of rise for such currents can be as high as 10^6 to 10^{12} A/s, and rise times can vary from few microseconds to few nano seconds. In all such cases the sensing device should be capable of measuring the signal over a wide frequency band.

The methods that are frequently employed are **(i) resistive shunts, (II) magnetic potentiometers or probes, and *(III)* the Faraday and Hall effect devices.**

Resistive shunts

The most common method employed for high impulse current measurements is a low ohmic pure resistive shunt shown in Fig. 7.45. The equivalent circuit is shown in Fig. 7.45b. The current through the resistive element R produces a voltage drop $v(t) = i(t)R$. The voltage signal generated is transmitted to a CRO through a coaxial cable of surge impedance Z_0. The cable at the oscilloscope end is terminated by a resistance $R_t = Z_0$



(a) Ohmic shunt (b) Equivalent circuit of the shunt

Fig. 7.45 Calibrated low ohmic shunt and its equivalent circuit for impulse current measurements

The voltage drop across the shunt in the complex frequency domain may be written as:

$$V(s) = \frac{(R + Ls)}{(1 + RCs + LCs^2)} I(s) \tag{7.35}$$

where s is the complex frequency or Laplace transform operator and $V(s)$ and $I(s)$ are the transformed quantities of the signals $v(t)$ and $i(t)$. With the value of C neglected it may be approximated as:

$$V(s) = (R + Ls)I(s) \tag{7.36}$$

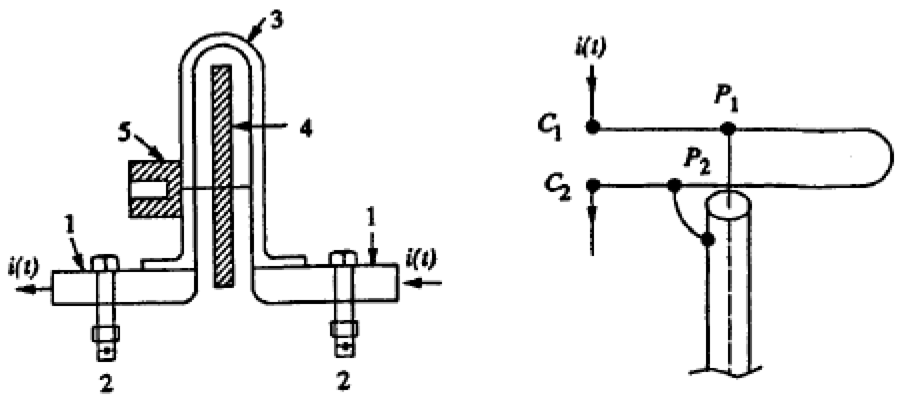
The resistance shunt is

usually designed in the following manner to reduce the stray effects.

(a) **Bifilar flat strip design,**

(b) **coaxial tube or Park's shunt design, and**

(c) **coaxial squirrel cage design**



(a) Schematic arrangement

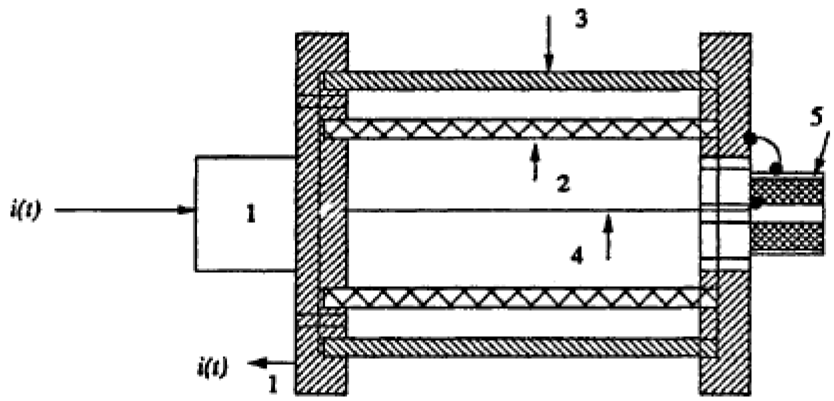
(b) Connection for potential and current terminals

1. Metal base
2. Current terminals (C_1 and C_2)
3. Bifilar resistance strip
4. Insulating spacer (teflon or bakelite)
5. Coaxial UHF connector
   P_1, P_2 — Potential terminals

Fig. 7.46 Bifilar flat strip resistive shunt

(a) Bifilar Strip Shunt

The bifilar design (Fig. 7.46) consists of resistor elements wound in opposite directions and folded back, with both ends insulated by a teflon or other high quality insulation. The voltage signal is picked up through a ultra high frequency (UHF) coaxial connector. The shunt suffers 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 measured. To overcome these problems, coaxial shunts are chosen.



1. Current terminals
2. Coaxial cylindrical resistive element
3. Coaxial cylindrical return conductor (copper or brass tube)
4. Potential pick up lead
5. UHF coaxial connector

(b) Coaxial Tubular or Park's Shunt

In the coaxial design (Fig. 7.47) the current is made to enter through an inner cylinder or resistive element and is made to return through an outer conducting cylinder of copper or brass. The voltage drop across the resistive element is measured between the potential pick-up point and the outer case. The space between the inner and the outer cylinder is air and hence acts like a pure insulator. With this construction, the maximum frequency limit is about 1000 MHz and the response time is a few nanoseconds. The upper frequency limit is governed by the skin effect in the resistive element. The equivalent circuit of the shunt is given in Fig. 7.48. The step response and the frequency response are shown in Fig. 7.49. The inductance L_0 shown in Fig. 7.48 may be written as:

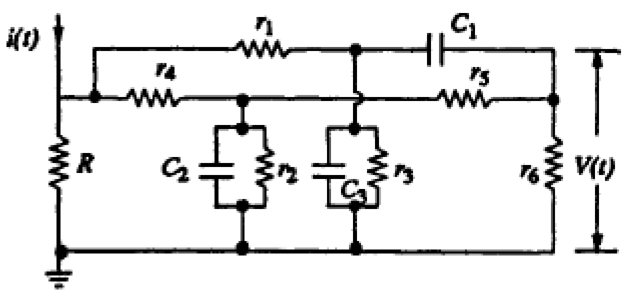
$$L_0 = \frac{\mu d l}{2\pi r} \tag{7.37}$$

where, $\mu = \mu_0 \mu_r$; the magnetic permeability, $\mu_0 = 4\pi \times 10^{-9}$ Vs/A cm is the magnetic field constant of vacuum

$d =$ thickness of the cylindrical tube,

(c) Squirrel Cage Shunts

In certain applications, such as post arc current measurements, high ohmic value shunts which can dissipate larger energy are required. In such cases tubular shunts are not suitable due to their limitations of heat dissipation, larger wall thickness, and the skin effect. To overcome these problems, the resistive cylinder is replaced by thick rods or strips, and the structure resembles the rotor construction of double squirrel cage induction motor. The equivalent circuit for squirrel cage construction is different, and complex. The shunts show peaky response for step input, and a compensating network has to be designed to get optimum response. In Fig. 7.50, the step response (Fig. 7.50a) and frequency response (Fig. 7.50b) characteristics are given. Rise times of better than 8 n s with bandwidth more than 400 MHz were obtained for this type of shunts. A typical *R-C* compensating network used for these shunts is shown in Fig. 7.51.



R — Shunt resistance
$r_1 - r_6$ — Resistors and capacitors in compensating double T network and $C_1 - C_6$

Fig. 7.51 Compensating network for squirrel cage shunts

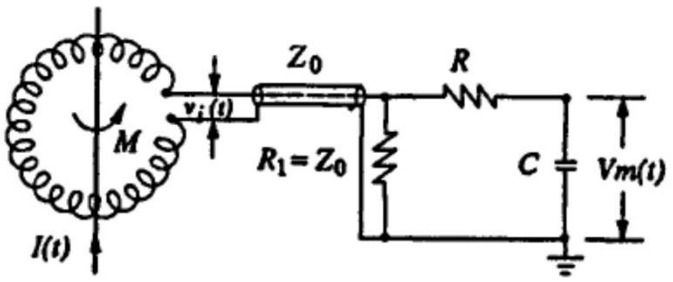
Rogowski Coils

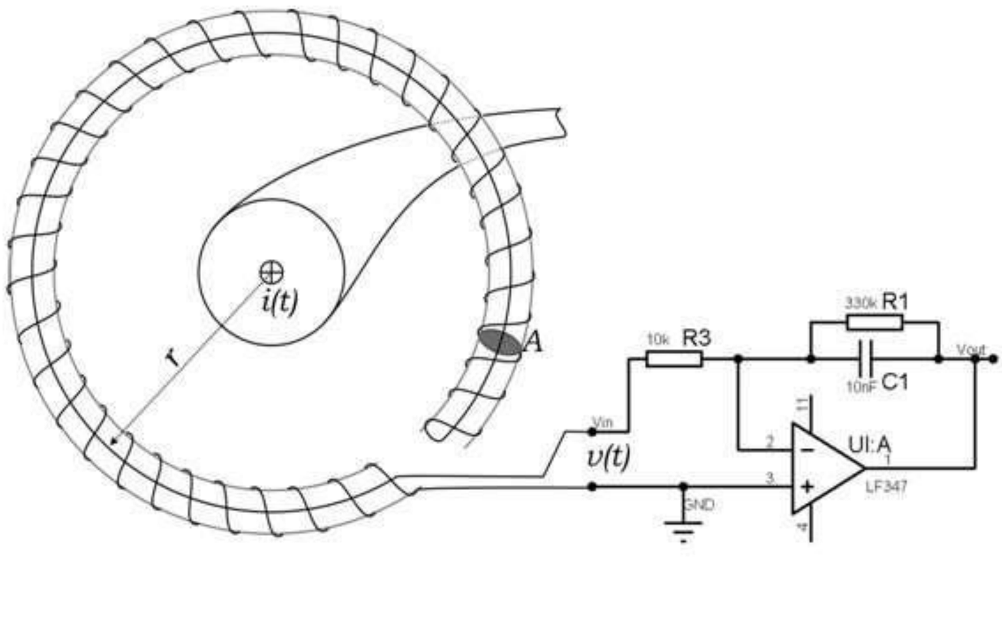
Measurement **of *high impulse current***

1. A Rogowski coil, named by Walte Rogowski, is **an electrical device for measuring Alternating Current(AC) or high speed current pulses.**
2. It consists of a helical coil of wire with the lead from one end returning through the centre of the coil to the other end, so that both terminals are at the same end of the coil.
3. The whole assembly is then wrapped around the straight conductor whose current is to be measured.
4. Since the voltage that is induced in the coil is proportional to the rate of change of current in the straight conductor.
5. There is no metal (iron) core.

"A Rogowski coil is a toroid of wire used to *measure an alternating current i(t)* through a cable encircled by the *toroid"*

1. **Connected to an electrical (or electronic) The output of the Rogowski coil is usually integrator circuit to provide an output signal that is proportional to the current**





Integrator circuit

2. Usually an integrating circuit RC is employed as shown in Fig to obtain the output voltage proportional to the current to be measured.
3. If a coil is placed surrounding a current carrying conductor, the voltage signal induced in the coil is

$$v_i(t) = M dI(t)/dt$$

M is the mutual inductance between the conductor & coil.

I(t) is the current flowing in the conductor.

4. ***The coil is wound on a nonmagnetic former of toroidal shape and is coaxially placed surrounding the current carrying conductor.***
5. **The number of turns on the coil is chosen to be large, to get enough signal induced.**
6. **The output voltage is given by**

$$V_m(t) = \frac{1}{CR}\int_0^t v_i(t) = \frac{M}{CR} I(t)$$

7. **Rogowski coils with electronic or active integrator circuits have large bandwidths (about 100 MHz).**
8. **At frequencies greater than 100 MHz the response is affected by the skin effect.**

Advantages

1. Lower construction costs.
2. Temperature compensation is simple.
3. No iron core to saturate

Disadvantages

1. **Maintenance of integrators circuit**

3.3.1 Magnetic Link

1. These can be used for measurement of peak value of impulse currents.
2. Magnetic links are high retentively steel strips arranged on a circular wheel or drum.
3. These strips have the property that the remanent magnetism (residual magnetism) for a current pulse of **0.5/5 µs** is same as that caused by a d.c. current of the same value.
4. Remenent magnetism or Residual magnetism is the magnetization left behind in a feromagnetic material after an external magnetic field is removed
5. The strips will be kept at a known distance from the current carrying conductor and parallel to it.

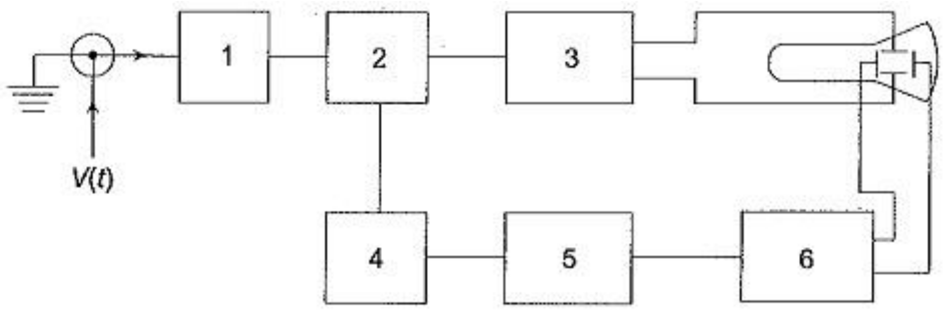
6. The Remanent magnetism (Residual magnetism) is then measured in the laboratory from which the peak value of the current can be estimated.
7. These are useful for field measurements, mainly for estimating the lightning currents on the transmission lines and towers.
8. By using a number of links, accurate measurement of the peak value, polarity, and the percentage oscillations in lightning currents can be made.

3.3.2 Cathode Ray Oscillograph for Impulse Measurements:

Modern Cathode Ray Oscillograph for Impulse Measurements are sealed tube, hot cathode oscilloscopes with photographic arrangement for recording the waveforms. The cathode ray oscilloscope for impulse work normally has input voltage range from 5 m V/cm to about 20 V/cm. In addition, there are probes and attenuators to handle signals up to 600 V (peak to peak). The bandwidth and rise time of the oscilloscope should be adequate. Rise times of 5 ns and bandwidth as high as 500 MHz may be necessary.

Sometimes high voltage surges test oscilloscopes do not have vertical amplifier and directly require an input voltage of 10 V. They can take a maximum signal of about 100 V (peak to peak) but require suitable attenuators for large signals.

Oscilloscopes are fitted with good cameras for recording purposes. Tektronix model 7094 is fitted with a lens of 1 : 1.2 polaroid camera which uses 10.000 ASA film which possesses a writing speed of 9 cm/ns.



1. *Plug-in amplifier* 2. *Y amplifier* 3. *Internal delay line*
4. *Trigger amplifier* 5. *Sweep generator* 6. *X amplifier*

With rapidly changing signals, it is necessary to initiate or start the oscilloscope time base before the signal reaches the oscilloscope deflecting plates, otherwise a portion of the signal may be missed. Such measurements require an accurate initiation of the horizontal time base and is known as triggering. Oscilloscopes are normally provided with both internal and external triggering facility. When external triggering is used, as with recording of impulses, the signal is directly fed to actuate the time base and then applied to the vertical or Y deflecting plates through a delay line. The delay is usually 0.1 to 0.5 μs.

The delay is obtained by:

1. A long interconnecting coaxial cable 20 to 50 in long. The required triggering is obtained from an antenna whose induced voltage is applied to the external trigger terminal.

2.The measuring signal is transmitted to the CRO by a normal coaxial cable. The delay is obtained by an externally connected coaxial long cable to give the necessary delay. This arrangement is shown in Fig. 7.55.

3.The impulse generator and the time base of the CRO are triggered from an electronic tripping device. A first pulse from the device starts the CRO time base and after a predetermined time a second pulse triggers the impulse generator.

Numericals

Example 7.1: A generating voltmeter has to be designed so that it can have a range from 20 to 200 kV d.c. If the indicating meter reads a minimum current of 2 μA and maximum current of 25 μA, what should the capacitance of the generating voltmeter be ?

Solution: Assume that the driving motor has a synchronous speed of 1500 rpm.

$$I_{rms} = \frac{VC_m}{\sqrt{2}}\omega$$

where, $V =$ applied voltage,

$C_m =$ capacitance of the meter, and

$\omega =$ angular speed of the drive

Substituting,

$$2 \times 10^{-6} = \frac{20 \times 10^3 \times C_m}{\sqrt{2}} \times \frac{1500}{60} \times 2\pi$$

$\therefore$ $C_m = 0.9$ p.F

At 200 kV, $I_{rms} = \dfrac{200 \times 10^3 \times 0.9 \times 10^{-12} \times 1500}{\sqrt{2} \times 60} 2\pi$

$= 20.0\ \mu A$

The capacitance of the meter should be 0.9 pF. The meter will indicate 20 kV at a current 2 μA and 200 kV at a current of 20 μA.

Example 7.2: Design a peak reading voltmeter along with a suitable micro-ammeter such that it will be able to read voltages, up to 100 kV (peak). The capacitance potential divider available is of the ratio 1000 : 1.

Solution: Let the peak reading voltmeter be of the Haefely type shown in Fig. 7.17a.

Let the micro-ammeter have the range $0 - 10\ \mu A$.

The voltage available at the C_2 arm $= 100 \times 10^3 \times \frac{1}{1000}$

$$= 100 \text{ V (peak)}$$

The series resistance R in series with the micro ammeter

$$= \frac{100}{10 \times 10^{-6}}$$

$$= 10^7 \Omega$$

$C_S R = 1$ to 10 s

Taking the higher value of 10 s, $C_S = \frac{10}{10^7}$

$$= 1\ \mu F$$

The values of C_S and R are $1\ \mu F$ and $10^7 \Omega$.

Example 7.3: Calculate the correction factors for atmospheric conditions, if the laboratory temperature is 37°C, the atmospheric pressure is 750 mm Hg, and the wet bulb temperature is 27°C.

Solution: Air density factor, $d = \frac{p}{760} \frac{293}{(273 + t)}$

At $t = 37°C$ $\quad d = \frac{750}{760} \frac{293}{310}$

$$= 0.9327$$

From Table 7.6 air density correction factor $K = 0.9362$. From Fig. 10.1, the absolute humidity (by extrapolation) corresponding to the given temperature is $18\ g/m^3$. From Fig. 10.2, the humidity correction factor for 50 Hz (curve *a*) is 0.925.

(Note: No humidity correction is needed for sphere gaps.)

Example 7.4: A resistance divider of 1400 kV (impulse) has a high voltage arm of 16 kilo-ohms and a low voltage arm consisting 16 members of 250 ohms, 2 watt resistors in parallel. The divider is connected to a CRO through a cable of surge impedance 75 ohms and is terminated at the other end through a 75 ohm resistor. Calculate the exact divider ratio.

Solution: h.v. arm resistance, $R_1 = 16{,}000$ ohms

l.v. arm resistance, $\quad R_2 = \frac{250}{16}$ ohms

Terminating resistance, $\quad R_2' = 75$ ohms

hence, the divider ratio, $\quad a = 1 + R_1/R_2 + R_1/R_2'$

$$= 1 + 16{,}000 \times 16/250$$

$$= 1 + 16{,}000/75$$

$$= 1 + 1024 + 213.3 = 1238.3$$

Example 7.6: A coaxial shunt is to be designed to measure an impulse current of 50 kA. If the bandwidth of the shunt is to be at least 10 MHz and if the voltage drop across the shunt should not exceed 50 V, find the ohmic value of the shunt and its dimensions.

Solution: Resistance of the shunt (max) $R = \dfrac{50}{50 \times 10^2}$

$= 1\ \text{m}\Omega$

Taking the simplified equivalent circuit of the shunt as given in Fig. 7.48(b)

Bandwidth $\qquad B = \dfrac{1.46R}{L_0} = 10\ \text{MHz}$

or, $\qquad L_0 = \dfrac{1.46R}{B} = \dfrac{1.46 \times 10^{-2}}{10 \times 10^6}$

$= 1.46 \times 10^{-10}\ \text{H}$

or 0.146 n H

d, the thickness of the cylindrical resistive tube is taken from the consideration of the bandwidth as

$$B = \frac{1.46\rho}{\mu d^2}$$

where,

$\rho =$ resistivity of the material,

$\mu = \mu_0 = 4\pi \times 10^{-7}$ H/m, and

$d =$ thickness of the tube in metres

Let $\qquad r =$ radius of the resistive tube,

$l =$ length of the resistive tube,

$d =$ thickness of the resistive tube, and

$\rho =$ resistivity of the tube material.

Then the bandwidth $\qquad B = \dfrac{1.46\rho}{\mu d^2}$

where, $\qquad \mu = \mu_0\mu_r \approx \mu_0$

Substituting $\qquad B = 10^7$ Hz

$\rho = 30 \times 10^{-8}\ \Omega\text{m}$

$$\mu_0 = 4\mu \times 10^{-7}$$

$$d = \sqrt{\frac{1.46\rho}{\mu B}}$$

$$= \sqrt{\frac{1.46 \times 30 \times 10^{-8}}{4\pi \times 10^{-7} \times 10^{7}}}$$

$$= 0.187 \times 10^{-8} \text{ m}$$

$$= 0.187 \text{ mm}$$

Let the length l be taken as 10 cm or 10^{-1} m;

then, $$R = \frac{\rho l}{A} = \frac{\rho l}{(2\pi r)d} = 1 \text{ m}\Omega$$

or, $$r = \frac{\rho l}{2\pi R d}$$

$$= \frac{30 \times 10^{-8} \times 10^{-1}}{2\pi \times 10^{-3} \times 0.187 \times 10^{-3}}$$

$$= 25.5 \times 10^{-3} \text{ m}$$

or 25.5 mm.

Example 7.7: A Rogowski coil is to be designed to measure impulse currents of 10 kA having a rate of change of current of 10^{11} A/s. The current is read by a VTVM as a potential drop across the integrating circuit connected to the secondary. Estimate the values of mutual inductance, resistance, and capacitance to be connected, if the meter reading is to be 10 V for full-scale deflection.

Solution: $V_m(t) = \frac{M}{CR} I(t)$ for $\frac{1}{CR} << \omega$ (Eq. 7.42),

taking the peak values

$$\frac{M}{CR} = \frac{V_m(t)}{I(t)} = \frac{10}{10^4} = 10^{-3}$$

The time interval of the change of current assuming sinusoidal variation is

$$\frac{10^4}{10^{11}} = 10^{-7} \text{ s} = \frac{1}{4} \text{ of a cycle}$$

$\therefore$ frequency $$= \frac{10^7}{4} \text{ Hz}$$

and, $$\omega = 2\pi f = \frac{\pi}{2} \times 10^7$$

Taking $$\frac{1}{CR} = \frac{\omega}{10\pi} = \frac{10^6}{2}$$

$$CR = \frac{2}{10^6}$$

$$M = 10^{-3}CR = 10^{-3}\frac{2}{10^6}$$

$$= 2 \times 10^{-9} \text{ H or } 2 \text{ n H.}$$

Taking $R = 2 \times 10^3\ \Omega$,

$$C = \frac{CR}{R} = 2 \times 10^{-6}/20 \times 10^2$$

$$= 10^{-9} \text{ F or } 1000 \text{ pF}$$

(It should be noted that for a given frequency, $X_c << R$; otherwise the low frequency response will be poor. Here X_c at $f = 10^7/4$ is 60Ω only.)

Course Outcome

At the end of the course, students will be able to:

CO-3: Apply measurement techniques for High Voltage, current and Impulse voltages.